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MINERALOGY AND ORIGIN OF THE TACONIC LIMONITES.

D. H. NEWLAND.

INTRODUCTION.

THE limonites of the Taconic district of New England and New York are part of the Cambro-Ordovician series, which extends in interrupted sequence along the Appalachians, to the west of older crystalline formations, from Nova Scotia to Alabama. They share a due part of the copious literature contributed by many workers in the last fifty years and more—a literature that is still open to further elaboration and discussion. On the matter of origin it appears that the treatment, notably by later writers, holds rather closely to the assumption that most limonites of the region are residual accumulations, associated as they often are with residual clays, ochers and manganese ores. As a rule, scant notice is paid in the contributions to their inherent features as geological materials. Weathering and leaching, obviously, are not exclusively confined to the country rocks. The textures, mineralogy and chemical traits of the ores seem to offer opportunity for a closer approach to the facts of their genetic history than has been attained thus far.

Present opinion favors the division of the Cambro-Ordovician limonites into two groups—mountain ores and valley ores. Whether a geological basis may be found for this distinction is rather problematic. Mountain ores are not restricted in occurrence to regions of deep rock decay like the valley ores, but that

circumstance may be fortuitous rather than essential from the methods of ore deposition. On exploration, the loose surface ores are frequently observed to pass in depth into compact aggregates in the shape of bands and lenses enclosed by rock walls, and these elongate bodies commonly follow the general structural trend. Some informed writers consider the mountain ores, at least representative examples, to be concentrations effected by meteoric circulations which have collected the iron and accompanying manganese from a wide region. Such explanation finds more or less support in the described field relations. The valley ores, on the other hand, for the most part confined to clays, pockety and shallow as a rule, are unreservedly held by geologists familiar with their field occurrence to be products of leaching and solution within the loci of the present deposits.

Whatever import the dual classification may have for other fields, within the Taconic belt it carries little, if any, significance. The most that can be said is that the Taconic ores show more of the characteristics outwardly of the mountain limonites, although they are restricted mainly to the limestone lowlands where the marks of weathering are at a maximum. They are not in any proper sense residual accumulations.

In the present study much use has been made of microscopic sections. Petrographical methods have been found to be applicable to selected materials, in fact they are indispensable in obtaining light on the origin of the deposits. It is probable that they may be employed to advantage on other limonite occurrences.

As a first step in this investigation, mention may be made of the recent examination of thin sections of the ores at Hudson, N. Y., in connection with Dr. Ruedemann's study of the geology of the area.

GENERAL FEATURES OF TACONIC DEPOSITS.

The limonites within the Taconic belt of eastern New York and western New England are associated with siderite—a feature shared by other Appalachian deposits. The siderite is found as remnant cores surrounded by the hydrous oxides, also as substantial discrete bodies which, according to contemporary mining

accounts, were likely to increase their proportions with depth. The relations lead one to infer that siderite is the parent source of much of the limonite. Some of the mine pits where siderite is known to occur in substantial amounts are at Richmond Furnace and West Stockbridge, Mass., Ore Hill, Conn., and Copake, Boston Corners, Amenia and Halstead, N. Y., all important sources of the mined ores. Another example, more informative for the geological student of to-day because of present accessibility of the workings, is the group of mines near Hudson, N. Y. These ores reappear in Vermont, where a succession of deposits is traceable at the western foot of the Green Mountains from Bennington north for an additional 75 miles or more.

The deposits near Hudson, in an area lateral to the main Taconic-Green Mountain uplift but still within the Taconic province, are exposed along the sides of a series of upland ridges. These have been deeply glaciated, and siderite is abundant. The limonite here is restricted to the surface weathered zone of post-Glacial origin, which is rarely more than a foot or two deep. Below this capping of brown ore, siderite occurs as the sole iron mineral, pyrite excepted, to the limits reached in past mining operations, 150 feet or more vertically and several times that horizontally, from the outcrop. In the present status of geological study no reason is apparent for separating the Hudson from the easterly ore belt, between which a general similarity of ore characteristics obtains. Aside from local variations observed in weathering effects, the main difference seems to be attributable to the more advanced deformational and metamorphic conditions that prevail in the eastern part of the Taconic belt, conditions affecting the wall rocks as well as the ores.

The individual deposits of the area have many features in common; they show a notable degree of uniformity in mineral and chemical composition; they are consistently manganiferous to the extent of one or two per cent.; their silica content is high, 10 to 20 per cent. as a rule, due in part to admixture with detrital quartz and feldspar, also in part, as observed in the Hudson district particularly, to the presence of amorphous silica in the

groundmass. Where the ores have escaped the intensive compression, granulation, and recrystallization incident to the Taconic disturbance, they carry appreciable amounts of a volatile hydrocarbon; some examples of the Hudson siderite are so charged with bituminous matter that they bear close resemblance to blackband iron ore. Sulphur combined in pyrite is a constant although always a minor ingredient.

The ore bodies, where well exposed, appear to be lenses or seams intercalated conformably within the stratified series of limestones and slates or schists. The actual stratigraphic sequence and the position of the ore in the series have yet to be worked out over most of the Taconic belt, as obliteration of fossil remains and intricate folding and repeated overthrusting make accurate mapping a work of great difficulty. Individual deposits have been mined on the outcrop for hundreds of feet, even up to half a mile, in continuous trench-like excavations. A series of such workings may extend end to end, with breaks in continuity, of course, for two or three miles.

Mostly, the ores have been mined in such open pits, which because of the loose ground on top are considerably wider than the ore outcrop. About 100–125 feet is the usual limit for depth. In a few mines, slopes were extended from the pit bottoms and the ore extracted for an additional distance along the dip. No definite instances of the ore having been bottomed by mining are to be found in the records. On one New York property under the writer's observation, a series of test holes was put down about 15 years ago to determine the subsurface continuity of the seam formerly exploited only on the outcrop. Ore was proved to a depth of 350 feet vertically and for two or three times that distance in the direction of the dip from the former workings, without apparent interruption to the seam.

The Taconic area has contributed a fairly substantial output. Few precise figures are obtainable at this time in regard to individual mine production, but operations were in progress over a period of about 175 years, starting about 1740. Mining began in Columbia county, N. Y., also in the Salisbury district of Con-

necticut, at around the latter date. Shifting economic conditions, not depletion of ore supplies, brought the industry to an end. The U. S. Tenth Census credited the three States of New York, Connecticut and Massachusetts—which is the relative order of their total ore contribution—with a yield of 245,328 tons of limonite in the year 1879–1880. The entire yield from the outset, estimated from all available data, seems to have been not less than eight or nine million tons. Many properties are known to have contributed from one hundred to five hundred thousand tons each, and the Hudson mines produced about a million tons, mostly carbonate, in a period of about 20 years.

Because of their moderate phosphorus and appreciable manganese content, the limonites enjoyed considerable favor for making iron and steel to withstand hard service, as for car wheels, tools and heavy machinery. A noteworthy feature of the Taconic ores, shared by many of the Appalachian ores elsewhere, is the small but persistent content of zinc. This is traceable to primary sphalerite in the ores. Beck[1] relates that the local furnaces a century ago built up in time a coating of zinc oxide within the stacks. A sample of the deposit from the Ancram (N. Y.) furnace showed on analysis 96.10 per cent. ZnO, the rest carbon and iron oxide. Poughkeepsie, Hudson and Peekskill in New York, and Salisbury in Connecticut, were the principal furnace centers, but slag heaps marking the sites of early charcoal furnaces are scattered widely over the mining area.

Physical Characteristics.

For purposes of petrographic study the limonites fall into two classes, rock ores and loose ores. This division accords with miners' usage. Rock ores result from direct alteration of siderite in place; they are coherent brown limonites, finely textured but not glassy, which preserve most of the incidental mineral ingredients in their original associations and arrangements. Thus, they simulate the physical traits of primary carbonate, if not always pseudomorphic in the sense of preserving the crystal

[1] Beck, L. C.: Mineralogy of New York, p. 33, 1842.

shapes of the ancestral iron components. Such rock ores, when sectioned, commonly provide indubitable evidence of their former state.

The loose ores include limonitic clays, ochers, and disseminations of nodular, stalactitic and granular "limonite" in earthy materials which represent the decay and wash of the country limestones and schists, in places intermixed with glacial debris. Their iron may come in part from leaching of the rocks, particularly the schists which carry more or less pyrite, but it results largely from the re-working by physical and chemical agencies of the iron in the ore bodies. It was the common experience in mining, if we credit contemporary accounts, for the loose or wash ore to give way in depth to solid ledges of limonite or carbonate, which necessitated a change from pick and shovel methods to drilling and blasting on the part of the operators.

Between the "limonite" derived by oxidation in place of the carbonate and the "limonite" resulting from leaching and solution with later redeposition, it is not difficult to discriminate when the separate traits are kept in mind.

Because of its situation lateral to the central zone of deformation and metamorphism of the Taconic earth block, the Hudson district, already referred to, retains much more of the original textures and mineralogy of the ores than does the eastern belt. The Hudson limonite and siderite may be taken as prototypes of the Taconic ores as a class; they afford clues to certain particulars of their mutual history which else would escape notice. They require, therefore, separate attention.

Hudson District.

Ore Occurrence.—The ore, predominantly carbonate, is in a single seam whose surface continuity is interrupted by folds and faults. The line of outcrop, altogether about four miles long north and south, lies 300–500 feet above the Hudson River and a mile or two to the east. Kimball [2] mapped the occurrences and

[2] Kimball, J. P.: Siderite-basins of the Hudson River Epoch. Amer. Jour. Sci. (3), vol. 40, pp. 159–160, 1890.

recognized a series of small anticlines and synclines which involve ore and wall rocks. The ore horizon has stretches in which ferruginous sandstone, recognizable by its iron-stained outcrop, takes the place of the carbonate. The foot wall as well as the hanging wall consist of siliceous limestone or limy grit, the latter broken or brecciated in places.

Ruedemann,[3] in a paper based on preliminary field work, described the deposits as occupying a conformable interbedded position in the stratified series, which, on the evidence of graptolites found in the vicinity but not in the immediate wall rocks, he assigned to the Normanskill beds of the Lower Ordovician. Later and more detailed study, of which the results await publication, shows the probable presence of an overthrust which has brought the ore and its rock environment into unconformable relations. A manuscript by Ruedemann and T. Y. Wilson relating to the area, which the authors have kindly made accessible at this time, describes the situation as follows:

> Underlying the ore-beds on the west are Nassau beds with their typical thin-bedded quartzite bands. Overlying these are the Bomoseen olive grits grading into the Schodack brecciated limestones, which in the middle carry the iron-ore beds at a continuous horizon. This is followed on the east by a narrow, discontinuous belt of Deepkill shale and Normanskill chert. The series therefore is a normal one from west to east across the iron-ore belt, beginning with the lowest, the Nassau beds in the west, and continuing to the highest, the Normanskill in the east. The mining sections indicate that the series forms a rather flat syncline, owing to the competent character of the ore-beds, succeeded by overturned folds farther east in the shaly beds. The contact of the Nassau beds with the Normanskill beds to the west of them has not been observed, but it is probable from the general structure of the region that it is formed by an overthrust plane.

In substance, the recent work by Ruedemann and Wilson indicates that the siderite-limonite ore occurs as a bedded layer in grits and siliceous limestone which are part of the Schodack formation near the base of the Cambrian as represented in this part

[3] Ruedemann, R.: Age and Origin of the Siderite and Limonite of the Burden Iron Mines near Hudson, New York. N. Y. State Mus. Bull. 286, pp. 135–152, 1931.

of the Taconic region. Their carefully worked-out conclusion holds important possibilities for the unravelling of Taconic stratigraphy, for it is a reasonable assumption, on the basis of uniform ore characteristics and broader features, that the deposits throughout are closely related and were formed under similar conditions.

The ore seam varies from 8 to 10 feet to 40 feet thick. It has been locally squeezed by regional forces and in one place may be seen to wedge out along an overriding thrust, which is accompanied by a wide crush zone. In the main Burden mines on the slopes of Mt. Thomas, Smock[4] reports the seam to have been mined to a depth of 140 feet by 1889. The mines had produced 450,000 tons of roasted ore (nearly 600,000 tons crude) up to that time. Shipments continued from the locality until 1901.

Ore Characteristics.—The carbonate from Hudson is much darker in color than that observed elsewhere in the Taconic region, gray to coal black, and so fine-grained as to appear almost vitreous in hand specimen. It has a smooth fracture, somewhat like chert, and is an exceptionally tough, resistant rock. Crystallinity is suggested to the unaided eye merely by a faint sheen which results from the collective mirroring by innumerable cleavages of microscopic size.

Specimens of the richer ore, that is, with little detrital matter, exhibit no marked tendency toward a plane-parallel arrangement of the constituents; the entrance of coarse quartz and feldspar, however, leads to a definite layered or bedded appearance, more marked because of color variation. Detrital admixture loosens the bond, increases the porosity, and opens the way to weathering influences. Consequently, the sandy layers are generally brownish in contrast to the gray or black of the normal carbonate.

The ore is free of magmatic infusion, the only addition from the outside being quartz, calcite, and dolomite, which occur as fillings of tension cracks and joints, introduced by ground-water circulations.

The limonite near Hudson consists altogether of the rock

[4] Smock, John C.: Iron Mines and Iron-Ore Districts in the State of New York. N. Y. State Mus. Bull. 7, pp. 64–65, 1889.

variety and represents the accomplishment of atmospheric weathering since Glacial time. There has been no re-working of the hard ore to form loose limonite or ochers.

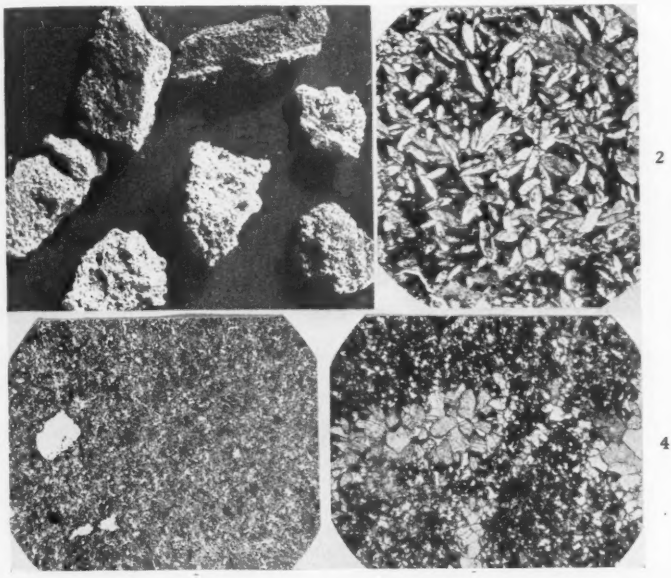


FIG. 1. Silica crusts after solution of the siderite in hot HCl. Those of lighter color show loss of the hydrocarbon by heating over gas flame. Hudson, N. Y. × 1.50.

FIG. 2. Siderite crystals in matrix of colloidal silica (black) and some silt. Hudson, N. Y. × 45.

FIG. 3. Finely crushed siderite with secondary sericite and larger fragmental quartz. West Stockbridge, Mass. × 45.

FIG. 4. Siderite, partly recrystallized, in process of change to limonite (black). Halstead, N. Y. × 45.

Microscopic Description.—Under the microscope the carbonate ore appears to be largely composed of idiomorphic siderite in minute rhombohedra, uniform as to size where found in the same layer, and closely packed without orientation. The interspaces are

filled with a greenish translucent colloid which has a passing resemblance to chamosite in its amorphous form. It has no cleavage and does not occur in crystal shapes, but is molded about the siderite. Its index of refraction is lower than that of siderite and higher than that of quartz. It carries more or less entangled silt. Qualitative chemical tests show that it is composed of silica for the most part, with a little ferrous iron and some carbon. Detrital quartz and feldspar, in particles much larger than the siderite crystals, and occasional bits of chlorite, muscovite and hornblende compose a widely varying fraction of the total. A dark coloring agent, evidently some form of hydrocarbon, is thinly dispersed through the mass.

By treating fragments of the ore in hot hydrochloric acid, skeletal crusts of the insoluble silica are obtained which hold molded impressions of the dissolved siderite. The crusts are nearly black but change quickly to grayish white in the heat of a gas flame. The organic matter thus appears to be a fairly volatile or combustible hydrocarbon (Fig. 1).

In most of the examples, the siderite is prevailingly of one type —slender, curved, doubly pointed crystals which because of their even shape and size resemble wheat grains (Fig. 2). The exception to be noted is the secondary siderite occurring in cavities and veinlets, where the form is more like the primary rhombohedron. The others approximate the flat rhombohedron $-\frac{1}{2}R$. Crystal aggregates or clots composed of a number of individuals held in a matrix of the amorphous silica and rimmed by a film of that substance are rare. Such clusters are difficult to explain except as formed in solutions saturated with the two components, the siderite moving about until entangled in the coagulating silica and then falling to the bottom, acquiring a coat of the silica on the way.

Detrital quartz and feldspar are to some extent disseminated throughout the ore but mostly they are gathered into distinct layers, which by alternation with the richer band produce a stratified structure apparent to the eye. Feldspar is close to quartz in abundance as a mechanical impurity; it is remarkably clear, as if unattacked by weathering.

Pyrite is the chief sulphide, although rarely abundant. It shows crystal shapes. A chance component, seen in one or two samples, is galena, clearly a primary component, contemporaneous with the siderite. The presence of sphalerite is suspected in view of the presence of zinc in the Taconic limonites elsewhere, but is not confirmed by identification.

In its content of colloidal silica and of dispersed hydrocarbon, the Hudson ore stands apart from other limonite-siderite occurrences of the region. In the writer's opinion, no fundamental distinction is involved; rather the difference is actually in line with the geological record of the two parts of the region, based as it is on the varying effects of metamorphism. The matter will be referred to again in the review of the evidences relating to the origin of the deposits.

In most of the siderite ore, there is little admixture of calcite and dolomite and their rôle is merely accessory. Dolomite is readily recognized by its straight-sided rhombs. Calcite, where present, lacks any definite shape. The relations of the three carbonates are those of independent components; they are never intergrown and show no evidence of mutual replacement.

Brecciation and mashing are local features, confined to the neighborhood of faults. Fracturing opened the way to infiltration of mineralizing waters charged with silica, lime and iron, likewise to weathering attack. The siderite has remarkable resistance to decomposition by surface agencies, for which the density of fabric and sealing of the pores by silt and amorphous silica may be held responsible in large part. The ability of the siderite ore to retain volatile organic matter under surface conditions is a further mark of this quality.

Texture and mineral associations as described are incompatible with theories of residual accumulation, replacement, or deposition in channels. The method of origin which alone meets the requirements in their entirety is that of chemical precipitation in open waters, a matter discussed more at length in connection with the Taconic ores as a whole.

Chemical Features.—Chemical analyses, of which several are

given by Raymond,[5] reveal no special features to distinguish the Hudson limonite and carbonate from ores of the rest of the district. The iron content of the crude carbonate runs from 32 to 38 per cent.; that of the roasted ore, above 45 per cent. The limonite has approximately the same composition as the roasted carbonate, after allowance for combined water. Silica is in substantial amounts, not under 14% as a rule; magnesia averages 2 or 3%, alumina upwards of 2.5%, lime less than 1.5% and manganese about 1%; phosphorus runs about 0.5%, and sulphur varies from less than 1 to over 2%.

The published analyses show no lead or zinc, but traces of these metals are doubtless present. Galena has been observed under the microscope, as already noted.

No manganese compound is to be seen, but this is not surprising. It is probable that the manganese, along with much of the magnesia and lime, exists in isomorphous mixture with the iron-carbonate molecule. In the process of limonitization the manganese is set free to form psilomelane and pyrolusite, which have a tendency to occur as separate concentrations.

The Eastern or Main Series of Taconic Limonites.

General Features.—Some 40 or 50 mine openings are distributed over a belt extending from Pittsfield, Mass., south along the interstate boundary to near Pawling, N. Y., in the heart of the classic Taconic area. The occurrences lie in the limestone lowland—limited east and west by ridges of phyllites and mica schists—which in Massachusetts is practically coterminous with the Stockbridge valley and in New York with the Harlem valley. A high schist ridge known as Washington Mountain, the culmination of the Taconic range in the area, intervenes between the Massachusetts part of the ore belt and that across the line in New York, but southward the two parts merge on the Connecticut-New York border, near Millerton, N. Y.

The areal geology of the region has not been satisfactorily worked out, although it has been under study for nearly a century.

[5] Raymond, R. W.: The Spathic Iron Ores of the Hudson District. Amer. Min. Inst. Trans., vol. 4, p. 341, 1876.

The basal rocks are gneisses of pre-Cambrian age, in part igneous. They are not found in immediate proximity to the ores. Above the gneisses is the Cheshire or Poughquag quartzite, including some quartz schists, assigned to the basal Cambrian. This formation also is not exposed so far as known within the main ore belt.

The strata which stand in close relation to the deposits are crystalline limestone and dolomite, phyllites and quartz-banded slates and mica schists. Most geologists, following J. D. Dana, have divided them into two main series—Stockbridge limestone for the carbonate rocks and Hudson River beds for the slates and schists, the former considered as Cambro-Ordovician and the latter as middle to late Ordovician. In recent years evidence has accumulated that the Hudson River slates and schists in their type occurrence are not a sequence limited to a single system, but include members that range from the lower part of the Cambrian to upper Ordovician, and it is not improbable that the same condition may hold in the terrane farther east.

A start toward detailed mapping has been made by Prindle and Knopf [6] in the Taconic quadrangle. Unfortunately, the mapped area does not fall within the limits of the main ore belt under consideration. The authors recognize in that quadrangle, which lies where Vermont, Massachusetts and New York corner, an overthrust series of Cambro-Ordovician quartzite, slates and schists, resting unconformably upon the limestone. If similar conditions hold in the area to the south, it is evident that the schists found above the ores are not necessarily younger than the limestones which underlie the ores for the most part.

In view of the intensive folding throughout the area, the stratigraphic order, as seen in any mine locality, also cannot safely be regarded as the normal arrangement even in the absence of overthrusting. The easterly dips of the ore bodies and wall rocks which prevail throughout the district suggest the presence of overturned anticlines and synclines, as has been remarked by Eckel.[7]

[6] Prindle, L. M., and Knopf, E. B.: Geology of the Taconic Quadrangle. Amer. Jour. Sci. (5), vol. 24, pp. 257–302, 1932.

[7] Eckel, E. C.: Limonite Deposits of Eastern New York and Western New England. U. S. Geol. Surv. Bull. 260, p. 317, 1904.

The strike is generally north or a little east of north, and the dip from 30° to 60° east. At Amenia, N. Y., one of the few places where the ore and wall rocks are well exposed, the succession across the dip from footwall to hanging wall is: limestone—ore—mica schist; with limestone repeated again to the east, above the schist. The limestone in the walls of the northern pit (Amenia mine) exhibits by contorted bands and flow structure evidence of considerable regional pressure and movement. The arrangement suggests overturning, in which case the mica schist is the underlying formation, but such view cannot at present be substantiated by other evidence.

In general, the ore bodies outcrop as straight narrow bands or seams without offsets. A few occurrences show displacement by longitudinal and cross faults. Hobbs[8] has given some instances of them, for example, at the Davis mine in Connecticut, where the deposit appears to occupy a down-faulted basin in the limestone. Again, at Ore Hill, near-by, he describes the ore as having a footwall of graphitic schist, which is intersected by a series of step-like faults that bring the schist into horizontal contact with the limonite. The Maltby mine in New York, with its nearly circular pit, shows a striking departure from the common lens or seam, due perhaps to faulting. It is notable that the few examples here cited are situated within the small area where the two limestone valleys, the Stockbridge and the Harlem, unite to the south of Washington Mountain.

Ore Occurrence.—The ore in most deposits is confined to a single unbroken layer, definitely demarcated from the bordering strata. It is unusual to find inclusions of limestone or schist within the ore zone, although in places a band of rock divides the seam into two layers. The bodies measure from 10 to 40 or 50 feet in thickness, 20 to 25 feet being average. Longitudinally and on the dip, the limits generally are indefinite, if explored at all beyond the actual mine openings.

Limonitization varies with local conditions, but is known to extend to depths of 200 feet or more in places. At Amenia and

[8] Hobbs, W. H.: Iron Ores of the Salisbury District of Connecticut, New York and Massachusetts. Econ. Geol., vol. 2, pp. 153–181, 1907.

West Stockbridge, on the other hand, ribs of carbonate reach well up into the oxidized zone and within a short distance of the surface, and at both places iron carbonate became the principal ore in later operations, the change at Amenia occurring at around or below 100 feet depth. At the Morgan mine, near Halstead, N. Y., the ore from the lower ground was limonite, but as the body was followed northward onto higher ground it turned to carbonate. Beyond that point the surface flattens again and it is reported that limonite reappears on the same line of strike, as proved by test drilling.

The general sequence of conditions from surface downward is: (1) drift, (2) ocherous sands and clays, (3) rock limonite, (4) siderite. The full sequence may not necessarily occur at any one mine. Unequal depth of pre-Glacial weathering and varying ice scour make for changes in the succession from place to place. As a rule, however, mining began with wash ore and wound up in hard limonite or carbonate. Variations in depth of weathering doubtless correspond to some extent with differences of structure or attitude of the bed, frequency of jointing, mashing effects, and other conditions not readily apparent at the present time. Deformation is largely responsible, no doubt, for the more extensive alteration of the eastern ores compared to those in the Hudson district.

It is quite evident that much of the weathering and oxidation effects, the greater part in all probability, is referable to pre-Glacial time. Siderite outcropping as a solid ledge withstands erosion and decomposition to a marked degree, especially when so finely textured and compact as in the Taconic district. The massive Hudson ore is still quite fresh and unaltered a foot or two from the glaciated surface, which is a measure of the progress of limonitization when not speeded up by favorable physical conditions of the ore and surroundings.

Siderite broken from the ledge and left on the ground exposed to the elements seems to decompose more rapidly than in the mine. Such is suggested at least by the behavior of an ore dump, some 40 or 50 years old, at the Morgan mine. Originally carbonate

or "white horse," it now appears upon casual inspection to be thoroughly oxidized, but actually, as observed in thin sections, the limonite is confined to a thin coating about the grains. Yet, frost and alternate wetting and drying in the weather are more effective in promoting disintegration than the influences at work upon the ore in the ledge.

Microscopic Description.—Superficially, the siderite from West Stockbridge, Amenia, and other eastern mines is distinguished by a dull, uniform gray color, suggestive of fine granular limestone rather than iron carbonate, a resemblance which might easily lead one to overlook its presence. The designation "white horse" by the miners is indicative of its appearance, although actually, it is medium gray or drab in color when unaltered. Absence of diffused bituminous matter accounts for its bleached appearance as compared to the dark Hudson ore. There is, however, a small amount of a coal-black substance, probably amorphous carbon, scattered as minute grains through the ore, too dispersed to have much effect upon the body color. Chemical analysis shows the presence of some free carbon.

Calcite and dolomite play little part in the composition of the ore, contrary to what would be expected if the iron were a replacement of the country limestones. In that respect the ores from the two parts of the Taconic district are alike. Siderite always predominates, to the practical exclusion of the other carbonates. These occur, however, as secondary fillings of cracks and vugs.

Pyrite is a constant associate but is never abundant. It is limited for the most part to microscopic specks and larger grains, the latter often with crystal outlines, irregularly disseminated or more rarely gathered in small veinlets, where it may be associated with vein quartz and dolomite. In general, the pyrite appears fresh in the unoxidized ore and there is no evidence of its replacing or being replaced by the siderite. The mining records do not seem to indicate any increase in the sulphide content with depth.

There is considerable fluctuation in the content of quartz and feldspar in mechanical admixture with the carbonate and limonite, just as has been noted in the Hudson ore. Stratification is not so apparent. The larger quartz particles are crushed into fragments and both quartz and feldspar often show pressure effects by their wavy extinction. The feldspar is sericitized (Fig. 3).

Weathering proceeds along the joints and incipient fractures, and is first noticed as a discoloration of the exposed surfaces. The conversion to ferric hydrate seems to take place molecule by molecule, with a shrinkage in volume corresponding to the difference in the molecular volumes of the two minerals. As weathering advances each particle of siderite becomes rimmed by "limonite" until a network of brown hydrate is formed which encloses the unaltered siderite grains, the threads gradually thickening with progress of oxidation until the whole mass, except for clastic quartz, sericite and feldspar, becomes rock "limonite" of granular habit. Such ore is somewhat porous, if not later soaked by iron-bearing waters so as to fill the vugs and shrinkage cracks with colloidal "limonite." The latter is distinctive by its reniform and banded appearance (Fig. 4).

The eastern Taconic ores carry no amorphous silica, so far as observed; but secondary sericite in threads and minute scales, also as aggregates of scales large enough to be called muscovite, is always present.

Locally, the wall-rock schists next to the ore show some impregnation by "limonite" so as to bear an off-hand resemblance to the real ore. The resemblance, however, is mostly superficial, as there has been little actual replacement of the body of the schist and the iron content is always low. The effect generally is little more than a discoloration. In many deposits the walls are not different from the schists at a distance. That the schists or limestones have been contributing factors to the ore deposition, either as sources of the iron or as materials replaced by it on a considerable scale, is an assumption for which the writer finds no substantial support in the field relations or in laboratory examination of the materials involved.

Chemical features.—Indicative of the main chemical features of the eastern Taconic ores, "limonite" and siderite, are the many analyses assembled by Hobbs,[9] largely from mining company records. More valuable for present purposes, however, are the few complete analyses given by Putnam[10] in the Reports of the Tenth Census. These show silica in amounts of from 10 to 25%, alumina to the extent of 3 or 4%, lime and magnesia together in amounts of 2 or 3%, and manganese from under 1 to above 2%. Each has a small content of free carbon, in addition to carbon dioxide; of the latter the percentages are a gauge of the extent of decomposition. Zinc is not shown in the analyses, but exists in traces, at least, as previously noted. Hobbs remarks in the paper cited that the siderite is low-grade, intermixed with silicates, but the analyses given by him of that material actually show from 30 to 45 per cent. iron, which is about the usual run for the siderite mined at Hudson; in equivalent terms of "limonite," they indicate ores of from 37 to 56 per cent. iron, which is about the proportions for limonites of the district. No doubt, some carbonate ore holds too much mechanical quartz and secondary sericite to be of furnace grade, but as a whole that of the pits corresponds closely in chemical composition to the derived "limonite."

In this as in the Hudson district the chemical evidence confirms the conclusion reached from microscopic examination as to the close correspondence between the siderite and the "limonite." Further, the analyses of the eastern Taconic ores as a whole show that they conform to type, with no individual aberrant examples suggestive of derivation apart from the rest.

PUBLISHED OPINION ON ORIGIN OF THE ORES.

Starting with J. D. Dana's descriptions of the geology and origin of the limonites, the literature reveals a wide range of view points on the processes involved in their accumulation, according

[9] *Op. cit.*, pp. 170–175.

[10] Putnam, B. T.: Notes on Samples of Iron Ore Collected in Connecticut, Massachusetts and New York. U. S. Tenth Census Reports, vol. 15, pp. 83–144, 1885.

to the emphasis placed on one or another circumstance or set of features in working out the problem. A brief resumé of the contributions follows.

Dana [11] regarded the siderite as a primary ore mineral and the deposits to be part of the sedimentary succession, closely related to the Stockbridge limestone. Besides siderite, which seems to have withstood decomposition to a marked extent, the original ore bodies may have contained isomorphous mixtures of iron, magnesia and lime carbonates, combinations that would more readily succumb to weathering attack. The age of the sediments is held to be Ordovician.

Kimball [12] explained the siderite ore near Hudson, which he recognized to be conformably interbedded in the stratified series, by deposition of ferric oxide in the evaporating waters of inshore basins along with organic matter and detritus. Later burial, with reduction of the ferric oxide in the presence of hydrocarbons, led to the formation of an interbedded layer of siderite; this mineral perhaps also replaced the wall limestone to some extent. He was the first, apparently, to recognize the possible relation of organic matter to the ore deposition.

Smock [13] remarked the presence of iron carbonate in the deeper workings of some of the Taconic pits. He considered the carbonate to be the source of the hydrous oxides.

Eckel,[14] in an introductory paper, not since extended, considered siderite the chief source of the limonite. Of the origin of the siderite he remarks that it was "deposited from solution and as a replacement of the limestone and not deposited in a basin contemporaneously with the inclosing rocks." Certain deposits where siderite is not visible in the pits (*e.g.*, Davis mines, Lakeville, Conn.) may have been formed by direct deposition of limonite from circulating underground waters.

[11] Dana, J. D.: On the Relations of the Geology of Vermont to that of the Berkshires. Amer. Jour. Sci. (3), vol. 14, pp. 132–140; also, Note on the Making of Limonite Ore Beds. Amer. Jour. Sci. (3), vol. 28, pp. 394–400, 1884.

[12] *Op. cit.*, pp. 159–160.

[13] Smock, J. C.: Geologico-Geographical Distribution of the Iron Ores of the Eastern United States. Amer. Inst. Min. Eng. Trans., vol. 12, p. 137, 1884.

[14] Eckel, E. C.: *Op. cit.*, 317–320.

Hobbs [15] developed the replacement idea further by considering the limonite and the carbonate as separate depositions, the one as replacement of the Berkshire schist and the other as replacement of the Stockbridge dolomite. The iron, in his view, came from some outside source, not from alteration of the ferruginous minerals in the immediate wall rocks, carried in solution as ferrous carbonate and sulphate. The time of ore deposition was probably late Glacial or post-Glacial. On that point no convincing evidence is provided and it is difficult to find any in the field.

Chance,[16] in a broad generalization on the origin of the Appalachian limonites—a thesis which leaves out of account most particulars about their geology and mineralogy—characterized them as gossans, the weathered outcrops of buried pyrite bodies. It is hard to find any factual support for the explanation from occurrences anywhere in the Taconic belt, although it is known of course that some deposits of the gossan type are found in the Appalachian region, notably in Virginia, North Carolina and Tennessee. Such, however, have quite different features from the usual run of Appalachian limonites, so as to be differentiated without much difficulty when they are explored or mined.

Ruedemann [17] reported the discovery of fossils of Normanskill (Lower Ordovician) age close to the ore zone of the Hudson mines. The deposits are stratified and contemporaneous, the siderite perhaps not deposited as such but derived from original magnetite by later chemical reactions within the beds.

THE EVIDENCE IN SUMMARY.

Microscopic examination, together with other information here brought out, gives new insight into the relations of the Taconic iron ores and the conditions of their origin. It may be remarked that the present study covers the occurrences in New York, Mas-

[15] *Op. cit.*, pp. 179–181.

[16] Chance, H. M.: Origin of the Limonite Ores of the Eastern United States. Amer. Inst. Min. Eng. Trans., vol. 39, pp. 791–808, 1909.

[17] Ruedemann, R.: Age and Origin of the Siderite and Limonite of the Burden Mines near Hudson, N. Y. N. Y. State Mus. Bull. 286, pp. 135–152, 1931.

sachusetts and Connecticut, but not those of Vermont, for which appropriate material has not been available.

The limonitized ores have a common heritage of characters due to their derivation from siderite as the principal source mineral. Siderite upon weathering yields rock limonite, which, like the former, occurs in bands or lenses intercalated conformably in the series of limestone and schists. The soft or wash ores are a step removed, as they consist for the most part of the re-worked outcrops of the hard limonite, supplemented to some extent, perhaps, by iron derived from leaching of pyritic bands in the schists. Between unaltered siderite at one extreme and the thoroughly oxidized ore at the other, every stage in the progress of weathering may be observed in samples collected from the mine pits. Rock limonites, owing to their inheritance of textural patterns and incidental mineral components of the originals, lend themselves to petrographic analysis for mutual comparisons and deductions as to origin.

Of the nature of the siderite bodies the evidence is conclusive for the Hudson occurrences in the western part of the Taconic belt. There the ores have been deposited as contemporaneous sediments of probably early Cambrian age. They have a stratified structure which extends to the finer layering of constituents. The siderite is in uniform crystal shapes and is associated with amorphous silica and plentiful organic matter in the form of diffused hydrocarbon, which latter produces a resemblance to blackband ore when concentrated, as it sometimes is, in definite beds. Well-rounded quartz, feldspar cleavages and silt compose the clastic sediment.

Definite sedimentary traits of texture and structure are rarely discernible in the eastern part of the ore belt because the deposits have shared the more intensive compression and metamorphism which characterize that area. It is obvious from this circumstance that the deposition of the siderite preceded the Taconic upheaval. Further, they show so many similarities—mineral, chemical and other—with the western deposits that little doubt arises that the eastern bodies are actually members of the same

group, formed under similar conditions. Mineralogically, the lack of amorphous silica and the presence of secondary sericite constitute the only distinctive features of the eastern ores, as compared with those found near the Hudson River.

Brecciation, mashing and metamorphism become more manifest as one crosses the Taconic belt from west to east. The ores follow the country in that respect. The clay shales of the western area give place to phyllites and to mica schists on the New England border.

Substantial differences are apparent in the extent of the limonitization from place to place. The process is slow under present static conditions and is practically confined to the zone above the water table. Fresh surfaces of siderite exposed by glacial erosion have since weathered to a depth of only a few feet. It is concluded that much of the limonite in the more substantial accumulations is pre-Glacial.

The manner in which the iron was collected and precipitated in the known associations and traits is a problem by itself. The occurrence of euhedral siderite with amorphous silica and organic matter in the described relations has few counterparts among the better known iron-ore deposits. The nearest analogy seems to be with the clay ironstone and black-band ores of the Carboniferous. There is little to be found in literature, at least within the writer's acquaintance, about the microscopic features of those ores, but it is inferred that the iron ore occurs as crystallized siderite with primary relations. Small amounts of manganese and traces of lead and zinc (rarely copper, nickel and cobalt) are indicated by analyses. So far, the resemblance is close. But the Taconic ores have only a minor content of clay and locally, at least, contain substantial amounts of colloidal silica. Further, the Taconic siderites attain a thickness of fully 40 feet, possibly more, in a single bed, much greater than the run of ironstones or black-band ores of our coal measures.

The deposition of the siderite took place most likely in lagoons or in-shore basins, which received wash from the land from time to time, as well as a steady influx of iron in solution. That the

iron was carried as ferrous bicarbonate seems probable. The abstraction of the solvent carbon dioxide by organisms, probably vegetable, caused precipitation, and the presence of free hydrocarbon has been one of the factors in preserving the iron in ferrous form. That the siderite crystallized before and not after precipitation is surmised from its relations with the silica.

Abundant stores of iron in the form of silicates and oxides were released by erosion of the crystalline formations in late pre-Cambrian time. The ferruginous minerals were largely decomposed and the iron taken into solution, for they do not appear to any notable extent as mechanical ingredients of the Cambrian sandstones and shales. Antecedent conditions, thus, may be held to have been favorable to the accumulation of chemically precipitated iron ores in the early Cambrian.

The relation of the Taconic district to the rest of the Appalachian district from the standpoint of the origin of the limonites is a subject for future examination. The outcome may be important for stratigraphy as well as economic geology. For the present it suffices to refer to the many striking comparisons between Taconic and other ore occurrences available in the published records, suggestive of a community of physical and chemical features hardly realizable from the operation of mere chance.

NEW YORK STATE MUSEUM,
ALBANY, N. Y.,
Oct. 24, 1935.

HYDROTHERMAL LEACHING IN THE VIRGINIA MINING DISTRICT, NEW MEXICO.[1]

SAMUEL G. LASKY.

ABSTRACT.

The tourmaline-copper deposits of the Virginia mining district, New Mexico, lie along veins that were plugged and reopened repeatedly during the process of mineral deposition. At some time between the second and third stages of deposition the solutions removed calcite, sericite, and chlorite from interstitial and included fragments of altered wall-rock in the veins and thereby produced honeycombed box-works of first- and second-stage minerals, chiefly specularite, quartz, and chalcopyrite, on the walls of which minerals of later stages were deposited. It is suggested that the leaching solutions may have been acid and that the leaching was done by the fresh solutions of the third stage before their acidity was neutralized through reactions along their channelways. A mechanism is suggested to account for their presence at places previously traversed by alkaline or neutral solutions.

INTRODUCTION.

THE term " hydrothermal leaching " is used here to mean outright solution and removal of material by hydrothermal solutions unaccompanied by deposition, or at least far outstripping deposition. The effects of such leaching have been observed in many epithermal deposits—as in the classic example at De Lamar, Idaho,[2] where early lamellar calcite was leached from an intergrowth with quartz to leave behind a delicate boxwork upon whose walls later minerals were deposited; and as at Cripple Creek, Colorado,[3]

[1] Published by permission of the Directors of the U. S. Geological Survey and the New Mexico Bureau of Mines and Mineral Resources.

[2] Lindgren, Waldemar: The Gold and Silver Veins of Silver City, De Lamar, and Other Mining Districts in Idaho. U. S. Geol. Survey, Twentieth Ann. Rept., Pt. 3, p. 170, 1900.

[3] Loughlin, G. F.: Personal communication. Also: Ore at Deep Levels in the Cripple Creek District, Colorado. Amer. Inst. Min. Met. Eng., Tech. Pub. 13, pp. 12–14, 1929.

where leaching took place at several stages of mineralization—but such effects have seldom been described for deposits of deeper-seated origin. The possibility that the process may have been of great importance in the formation of some deep-seated deposits has been considered by geologists, however, for the idea forms the foundation of Locke's theory of "mineralization stoping," [4] and Gruner [5] explains concentration of iron ores in the Lake Superior region by preferential hydrothermal leaching of the silica.

According to Ferguson,[6] some of the vacuoles in the vein quartz of the Alleghany district, California, are the result of solution. C. S. Ross [7] describes an example of "mineralization stoping" along the Gossan lead in Virginia subsequent to an aplite-pegmatite stage that initiated the mineralization sequence; and Landes [8] emphasizes the conclusion that open spaces in pegmatites have been "formed through the solvent action of hydrothermal solutions." In the Tucson mine, at Leadville, Colorado,[9] the quartzite host rock was corroded before deposition of the mesothermal ore deposits, and a similar situation exists at Tintic, Utah,[10] where some of the cavities in the jasperoid were probably formed by corrosion prior to the second stage of deposition. These few examples serve to indicate the wide range of occurrence of hydrothermal leaching, and it is possible that the process

[4] Locke, Augustus: Formation of Certain Ore Bodies by Mineralization Stoping. ECON. GEOL., vol. 21, pp. 431–453, 1926.

[5] Gruner, J. W.: Hydrothermal Oxidation and Leaching Experiments; their Bearing on the Origin of the Lake Superior Hematite-Limonite Ores. ECON. GEOL., vol. 25, pp. 697–719, 837–867, 1930. Additional Notes on Secondary Concentration of Lake Superior Iron Ores. ECON. GEOL., vol. 27, pp. 189–205, 1932.

[6] Ferguson, H. G.: Gold Quartz Veins of the Alleghany District, California. U. S. Geol. Survey, Prof. Paper 172, pp. 41–44, 1932.

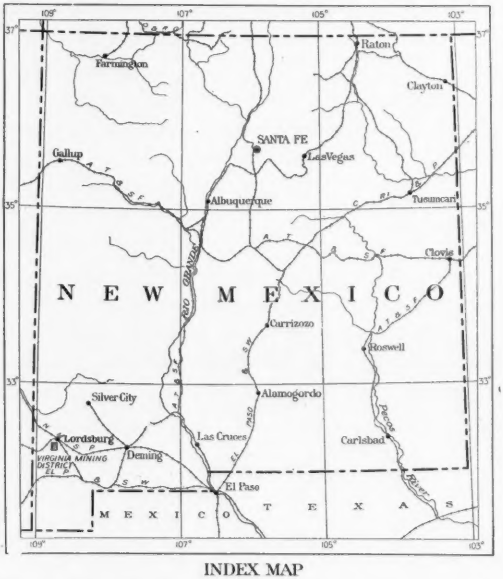
[7] Ross, C. S.: Origin of the Copper Deposits of the Ducktown Type in the Southern Appalachian Region. U. S. Geol. Survey, Prof. Paper 179, pp. 84–85, 1935.

[8] Landes, K. K.: Criteria of Age Relations in Minerals. ECON. GEOL., vol. 27, p. 211, 1932.

[9] Emmons, S. F., *et al.*: Geology and Ore Deposits of the Leadville Mining District, Colorado. U. S. Geol. Survey, Prof. Paper 148, pp. 289–291, 1927.

[10] Lindgren, Waldemar, and Loughlin, G. F.: Geology and Ore Deposits of the Tintic Mining District, Utah. U. S. Geol. Survey, Prof. Paper 107, p. 157, 1919.

has been much more common than has been reported. Any cavities produced by leaching are likely to be obscured or obliterated by later phases of deposition or vein movement, and only under extreme or favorable conditions may they be preserved well enough to be recognized readily. An excellent example of hydrothermal leaching well within the general period of vein formation has been noted by the writer in the tourmaline-copper veins of the Virginia mining district of New Mexico (Fig. 1),



INDEX MAP

FIG. 1. Map of New Mexico, showing location of the Virginia mining district.

and a description of the occurrence may be of interest to economic geologists.

The Virginia district has been studied under a co-operative agreement between the United States Geological Survey and the

New Mexico Bureau of Mines and Mineral Resources, and a detailed report is in preparation.

The writer is indebted to G. F. Loughlin and C. S. Ross for a critical reading of this manuscript, as well as to several others for informal discussions of the occurrence.

GENERAL GEOLOGY OF THE ORE DEPOSITS.

The following summary of the geology of the ore deposits is given as a necessary background to the description and discussion of the leaching features.

The Virginia district occupies the northern part of the Pyramid Mountains, one of the isolated desert ranges typical of the southwestern United States. The oldest rocks exposed are basalt flows, of Comanche (?) age and at least 2,000 feet thick, cut by plugs of basaltic and rhyolitic breccias and by plugs of white rhyolite. An irregular stock of granodiorite, accompanied by dikes of granodiorite porphyry and aplite, is intruded into the volcanic rocks. Dikes of quartz latite and felsite cut the other rocks, and Miocene (?) volcanic rocks are extensively exposed south of the district, where they are separated from the other rocks and from the veins by a major unconformity. Figure 2 shows the geology of the main part of the district.

The veins lie along fault zones of small displacement, in fissures that were reopened repeatedly during the process of mineral deposition, as shown by the presence of shattered and brecciated earlier minerals cemented by later ones. Movement took place in at least seven stages, counting the original opening of the fissures and post-ore movement along them. Each reopening during mineralization was accompanied by a distinct change in the character of the vein matter deposited, and there are shoots in which a particular variety of filling predominates. Figure 3 shows the distribution of the minerals of some of the different stages along the most thoroughly prospected vein in the district; the general impression gained from this illustration is that the channels followed by the solutions of any stage were in large part independent of those of any preceding stage. At no stage, except

possibly the first, were the vein openings filled completely, and the composite filling, representing all stages, is generally a highly vuggy and drusy mass containing fragments of altered wall-rock and of vein matter. The deposits contain an average of 1.2 ounces of silver and 0.1 ounce of gold a ton and 2.8 per cent of copper.

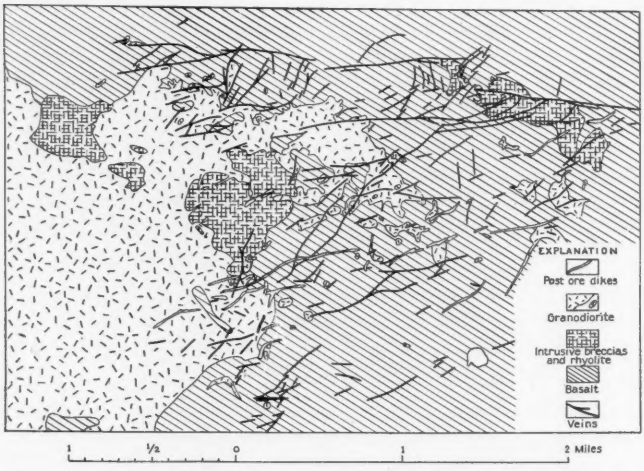


FIG. 2. Generalized geologic map of the main part of the Virginia mining district, New Mexico.

Figure 4 summarizes graphically the mineral succession in the veins and the relation of mineral deposition to other events. The six stages shown are as follows:

1. Sericitization, chloritization, and calcitization of the wall rocks, impregnation of the wall rocks by tourmaline and specularite, and deposition of tourmaline and specularite in the vein openings.

2. Reopening of the veins, with some sheeting and brecciation, followed by deposition of quartz and a little pyrite, which were accompanied at first by a trace of chlorite, then by considerable coarse-grained and massive chalcopyrite and a little mangano-

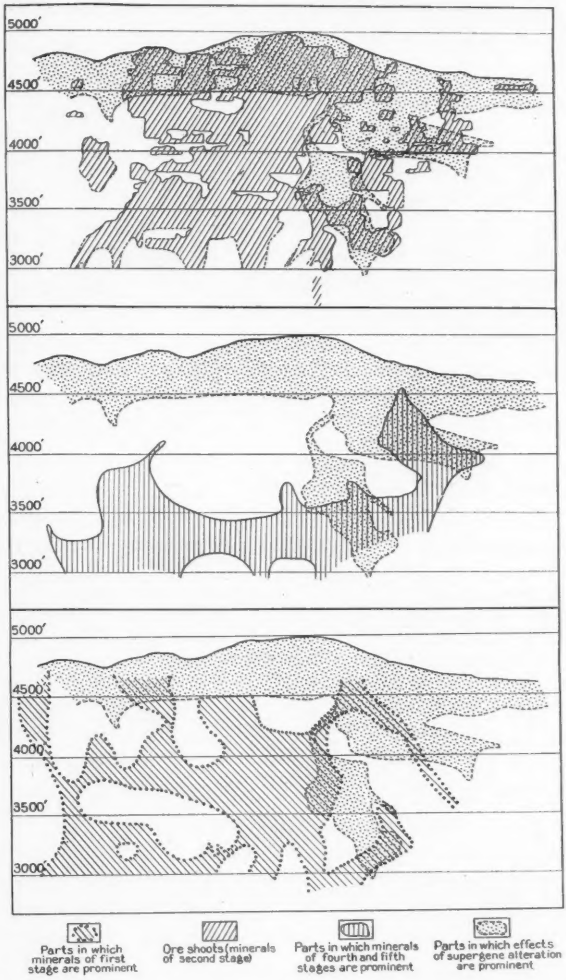


FIG. 3. Generalized longitudinal projection of the Emerald vein at the Eighty-five mine, showing distribution of vein filling of some of the hypogene stages and of supergene alteration. The ore shoots show the distribution of filling of the second stage.

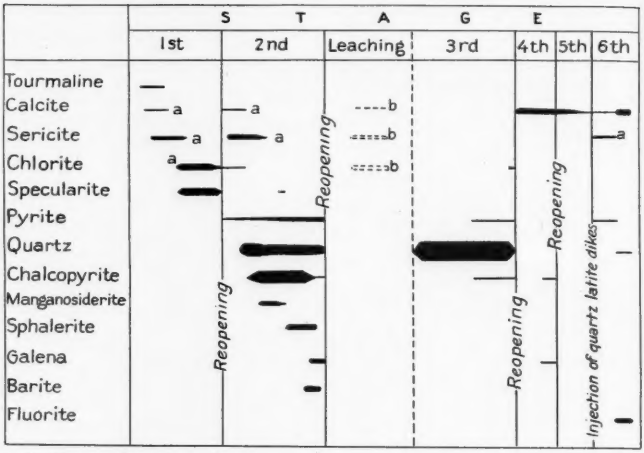


FIG. 4. Diagram showing mineral succession in the Virginia mining district and the relation of mineral deposition to other events. Average composition of the ore shoots: Quartz, 68%; sericite and chlorite, 8%; calcite, 5%; tourmaline and barite, 3%; manganosiderite, 0.5%; chalcopyrite, 8%; pyrite, 4%; specularite, 2%; sphalerite, 1%; galena, 0.5%.

siderite, and still later by sphalerite and minor amounts of galena and barite. The quartz is generally white and coarse-grained but includes fine-grained sugary aggregates and horny or cherty varieties that are largely silicified rock. Wall-rock alteration consisted of sericitization, silicification, and subordinate calcitization, which partly destroyed the earlier tourmaline and specularite. The exploitable ore deposits were formed during this stage.

3. Reopening and further brecciation, providing access for solutions of the third stage. The minerals deposited during this stage included abundant quartz, a very little chalcopyrite and pyrite, and a trace of chlorite. The quartz is a glittering, colorless to white, crystalline variety that grows in drusy masses looking much like rock candy, and forms knobby and bristling coatings on nearly all exposed surfaces. At places where the open

spaces have been filled, and in the core of the knobby masses, the quartz is milk-white and the crystals are compactly intergrown. Small crystals and crystalline clusters of chalcopyrite and pyrite are sparingly distributed through the quartz and characteristically form part of the crystal lining of the numerous cavities. At a few places minute flakes of chlorite crust the crystals of the cavities and tend to form grapelike clusters of tiny nodules. Silicification of the walls during this stage is largely the cause of the prominent wall-like outcrops of some of the veins.

4. Reopening, followed by partial cementation with pink manganiferous calcite, which is most abundant as scalenohedrons as much as 2 or 3 inches long lining the walls of cavities. Locally the calcite is accompanied by minor chalcopyrite and galena.

5. Reopening, followed by deposition of calcite only. This calcite is similar in composition, crystal form, and occurrence to the pink calcite of the preceding stage, but is gray to white.

6. Deposition of minor amounts of quartz, calcite, and fluorite, and alteration (sericitization, calcitization, and pyritization) of the quartz latite dikes, which were injected between this and the preceding stages.

Supergene alteration of the ores is irregular. High-grade gold and copper ores have been mined, but enrichment at one place has been balanced largely by leaching at another. The supergene suite comprises the usual minerals, a little wulfenite and calcite, and a trace of cuprodescloizite.

HYDROTHERMAL LEACHING.

General Description.

Between the second and third stages of deposition, parts of the veins were traversed by solutions that removed chlorite, calcite, and sericite from breccia fragments and slivers of altered wall rock, from interstitial rock matter in replacement masses of sulphides, and from some of the cherty silicified rock, leaving behind honey-combed masses of first- and second-stage minerals. The leaching of the breccia fragments produced large angular

cavities preserving the shape of the rock pieces that had occupied them. Rigid paper-thin ribs of vein matter, chiefly quartz and specularite, project into some of the cavities, and a comparison of these cavities with unleached breccia pieces indicates that the ribs were veinlets that originally cut the rock pieces. The walls

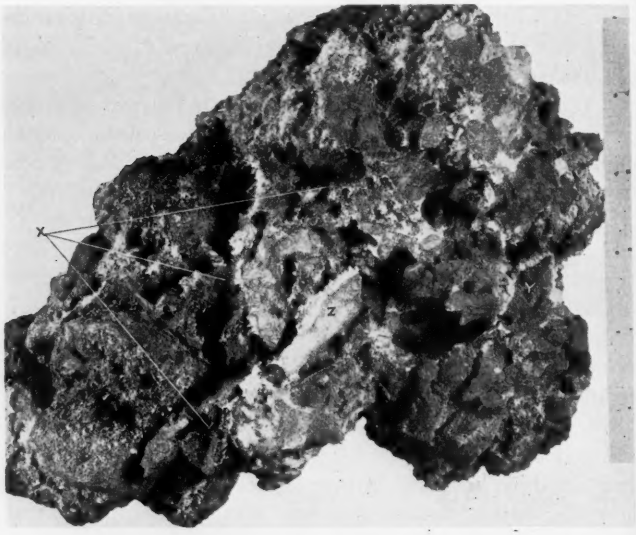
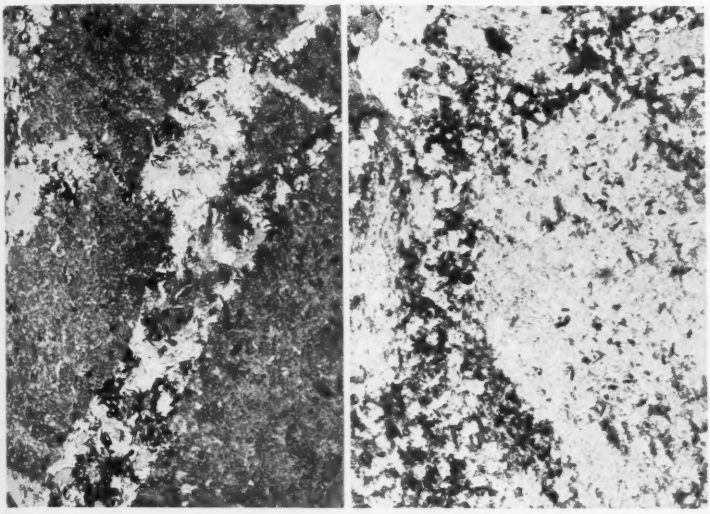


FIG. 5. Breccia ore from which rock fragments were leached prior to third-stage deposition; consists of specularite, quartz, chalcopyrite, a little barite and residual rock. Note angular shape of cavities with ribs of vein matter penetrating them (*e.g.* *X*). At *Y* the grains of quartz and specularite that impregnated the breccia fragment were sufficiently abundant to support one another after the rock matrix was removed; compare *Z*. Eighty-five mine.

of some cavities are marked by parallel striae, which presumably are the casts of slickensided surfaces of the breccia pieces. Figure 5 shows a typical piece of leached breccia ore.

Where the grains of quartz, specularite, and chalcopyrite that impregnated the altered rock were sufficiently abundant to support

one another after the rock matrix was removed, the result of leaching is a fine-textured honeycomb of those minerals. In some specimens the honeycombs fade into altered rock, and stringers of quartz, specularite, and chalcopyrite can be traced through rock into and across adjacent honeycombed parts. Some parts of the honeycomb are made up of fragile unoriented intergrowths that preserve the intergrowth of the same minerals in



A *B*

FIG. 6. Photomicrographs showing altered rock from which honeycombs such as those shown in Figs. 5 and 7 were derived.

A (left). Chloritized, sericitized basalt cut by veinlets of quartz and specularite, which form the walls of the honeycomb after the rest of the rock is removed. Thin section of breccia piece from Fig. 7. Plain transmitted light, × 10.

B (right). Altered granodiorite; original plagioclase phenocrysts replaced by sericite (light-gray felted areas); nonquartzose parts of groundmass replaced by chlorite and subordinate sericite (mottled, dark interstitial material); rock impregnated with specularite (black), which is confined largely to the chloritic groundmass. Clear white is residual quartz. Plain transmitted light, × 28.

the altered rock; other parts contain continuous ribs or walls that preserve the distribution of stringers originally cutting the rock. The quartz of the honeycombs is feathery and without regular structure, and lacks the crystal terminations of quartz deposited in open spaces, although it is in part coated with well-terminated quartz crystals of the next stage of deposition. Figures 6-*A* and 6-*B* show the character of the altered rock from which the honeycombs were derived, and Fig. 7 shows a fragment of honeycombed ore from which the thin section in Fig. 6-*A* was cut.

The honeycombs in the leached cherty, silicified rock are similar to the feathery quartz honeycombs described above, although naturally more quartzose. The cavities are quite distinct from the typical quartz-lined shrinkage druses present elsewhere in the silicified material.

The walls of the honeycomb cavities and the thin ribs in them are coated at places with minerals of the third stage of deposition —a fact that fixes the relative age of the leaching.

Distribution.

The honeycombs seem to be widely distributed in the veins, in the same sense that minerals of any particular stage are widely distributed, although with the difference that leaching seems to have been much more common in the altered basalt than in the altered granodiorite. It is possible that leaching was more prominent in general than now appears, for the honeycombs may have been crushed beyond recognition at some places during one of the several stages of later movement along the veins, or they may have been obscured or obliterated here and there by later deposition. Although the walls of the cavities are crusted at some places by later minerals, at others they are uncrusted, and it is reasonable to infer that at still other places the cavities are filled completely. The irregular distribution of leaching and of later minerals in the cavities fits the conclusion, as stated in a preceding paragraph, that the solutions of each stage of deposition tended to follow independent paths along the veins.

Character of the Leaching Solutions.

It seems unlikely that any changes in temperature or pressure alone could have caused outright solution of sericite, chlorite, and calcite from the altered rocks instead of their replacement by other minerals; on the contrary, it is believed that the leaching must have been done by solutions that differed chemically from

FIG. 7. Fine-textured honeycomb of quartz, specularite, and chalcopyrite, produced by leaching of the rock in which these minerals were distributed. Note the "gnawed" outlines of some of the rock pieces and the incipient honeycomb in the upper part of the piece at the right. Bonney mine. (See Fig. 6-*A*.)

those of the preceding stage of mineralization, for they dissolved minerals that had been formed by earlier solutions. The current trend among students of ore deposition seems to be toward the belief that ore-forming solutions may leave their magmatic source, at least in part or under special conditions, as acid gases that sooner or later may condense to yield acid solutions, which gradually become neutral or alkaline through reaction with the wall rocks.[11] Such acid solutions could readily dissolve minerals

[11] Fenner, C. N.: Ore Deposits of the Western United States. Amer. Inst. Min. Met. Eng., Lindgren volume, pp. 58–106, 1933.
Bowen, N. L.: *Idem*, pp. 118–128.

like those removed from the veins of the Virginia district. To judge from laboratory reactions and from general behavior in the zones open to observation, sericite is a more stable mineral than chlorite, and this difference may account for the greater corrosion of the altered basalt, which consists largely of chlorite, than of the altered granodiorite, which consists largely of sericite and quartz.

The structural history of the veins suggests a mechanism whereby acid solutions could have reached places traversed at earlier stages by neutral or alkaline solutions. As already described, the vein openings were incompletely filled during any one stage of deposition, and the material deposited during each stage differed from that of the preceding stages. From these features it may be inferred that the solution channelways of each stage became plugged somewhere near the source of the solutions before higher parts were completely filled, and that further deposition was delayed until the solution reservoirs were retapped by later movement along the vein fissures. Under those conditions a back pressure would be built up in the reservoirs during each stage of plugging, and it would seem possible that the solutions freed by the reopening that followed the second stage could have rushed into the fissures with such velocity that they traveled an abnormal distance before their acidity was neutralized. Perhaps, too—and this may be the more important—the vein fissures remained plugged at that stage long enough for the back pressure to be built up sufficiently to permit particularly effective distillation of volatile acid constituents—Bowen's "fractional distillation-column" [12]—when the pressure was released by renewed movement along the vein fissures.

Conceivably, the leaching may have been done by solutions of any one of three stages: (1) by late stagnant solutions of the second stage of deposition, (2) by independent solutions between

Emmons, W. H.: On the Origin of Certain Systems of Ore-bearing Fractures. Amer. Inst. Min. Met. Eng., Tech. Pub. 561, pp. 8–11, 1934.

Ross, C. S.: Oral communication.

The papers cited contain numerous other references.

[12] Bowen, N. L.: *Op. cit.*, pp. 122–124.

the second and third stages, or (3) by the fresh solutions of the third stage. The first suggestion seems extremely improbable. Of the remaining two, the third is the more favored, if only for the reason that it fits more compactly into the general picture. Under the third suggestion, the minor amount of chlorite that was deposited at the end of the third stage of deposition may be chlorite dissolved at the beginning of that stage, transported, and redeposited elsewhere.

U. S. GEOL. SURVEY,
SOCORRO, NEW MEXICO,
Aug. 21, 1935.

ORE-BODY ZONING.

L. B. RILEY.

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INTRODUCTION.

LARGE-scale zoning of minerals and metals about some center, such as a batholithic cupola, has been described for numerous districts, and Cornwall, England, and Butte, Montana, have come to be classic examples. Less attention, however, has been directed to the more restricted zoning about and in individual ore bodies. Certain features of such zoning have long been recognized and utilized, such as certain types of wall-rock alteration and contact-metamorphic aurioles. It is to this small-scale type of zoning that I wish to direct attention and for which I propose the term *ore-body zoning*. By this term is meant the spacial variation of minerals and elements about and within ore.

Some of the variations, such as sericitic alteration, can be detected by a trained eye and have to some extent been mapped and utilized by mine geologists. But many, perhaps the majority, of variations are not so readily discernible, and special means must be employed to detect them. A simple method by which

such variations may be detected and utilized is presented herewith.

It is obvious that any change around an ore body which shows consistent variation may serve as a guide to ore and thus be of pronounced economic importance to mine operators; and that the accuracy of such variations as guides is increased by the number of variations recognized. The miner with a "nose for ore" has used ore-body zoning to advantage; his "hunch" as to the location of ore is based on keen observations, coupled with past experience. But he depends on memory and visual observations. The mine geologist is better equipped to study the variations through his greater knowledge of mineralogy, realization of underlying principles, the time and opportunity to make supplementary tests and to record his observations on precise maps. All these advantages may be combined into a method, such as the one here proposed, specifically directed to the determination of the local ore-body zoning. These detailed studies in turn increase the geologist's ability to find ore, and thus increase his value to the mining industry and incidentally his own economic value as a company geologist.

The method proposed here shows how the maximum number of useful variables may be detected and how they vary spacially around an ore body. Those that form an auriole or halo beyond the limits of the ore proper, yet show measurable and consistent variation within that zone are considered the most important. They enlarge the target and so aid in finding the bull's-eye. Workings or diamond-drill holes may pass close to ore without that ore being discovered, yet the variables of the auriole might be apparent within these—the workings or diamond-drill hole have cut the edge of the target. In a similar way, unprofitable development work may be avoided.

METHOD OF STUDY.

The method consists of the determination and estimation of small quantities of a large number of elements and minerals, as suspected variants, using numerous small samples from recorded locations. The emphasis is on a large number of variables rapidly

determined from a large number of specimens. The large number reduces the errors not only from the technique of sampling and analyzing, but also from inconsequential local variations.

First, the rocks outward from a known ore body are sampled at intervals. These are tested by rapid methods, such as microchemical tests, for diagnostic elements and minerals, and the approximate amounts of each are recorded. The data so obtained are plotted graphically to show the relative variation of each element or mineral outward from the ore. A rough type diagram of the ore-body zoning is thus established for a particular locality. A similar diagram is determined during a new development. A comparison of this new diagram with the type diagram may point the way to unknown ore.

The proposed method will be illustrated by a specific example. But it is to be understood that the general method is applicable to most ore deposits, whatever their nature. Details would necessarily be modified according to the type of deposit; instead of the microscopic-microchemical method described below, other methods of analysis might be used, such as precise quantitive analysis, or spectrographic analysis. It has been found, however, that the methods using the microscope are both rapid and economical, and are sufficiently accurate. Further, the equipment is inexpensive, especially as compared to spectrographic methods. No elaborate, or even permanent, laboratory is required; microscopic methods of analysis can be adapted, with a minimum of effort, for field use.

The example chosen for illustration is an incompletely oxidized silver-lead ore body studied by the writer at Sierra Mojada, Coahuila, Mexico. The tests were worked out in the Laboratory of Economic Geology, Yale University. The ore is located along a portion of a nearly vertical fracture at its intersection with a favorable bed of a gently dipping limestone-dolomite formation. The strike of the formation is essentially parallel with the strike of the fracture. The exposures were in a drift extending from barren and only slightly altered limestone wall-rock, across the ore, and continuing into barren wall-rock beyond.

DETERMINATION OF VARIABLES.

Sampling.

A relatively large number of small "chip" or "hand specimen" samples were taken, with attention to the location of each. No particular care was used in the actual sampling beyond that the sample appeared reasonably representative of the area at that location; it is the variation in space that is important. Local variations and even local reversals in trend as well as compensating errors in technique are overcome by the number of samples taken.

Methods of Testing.

The samples were tested by optical and microchemical means. Although this scheme was devised for oxidized ores, many features may be used with advantage for studies of zoning in other types of ore bodies.

The procedure involves first, a partial decomposition of a portion of each sample by treating it with hydrochloric acid. This treatment yields three products: liberated gases, solution and insoluble residue. The solution is tested for its contained ions by about a dozen simple microchemical tests. The insoluble residue is examined by optical methods, supplemented by microchemical tests. Prior to this acid treatment the samples were mostly either too fine-grained or the grains were so coated with opaque oxides that the individual minerals could not be recognized either megascopically or by the usual methods of microscopic preparation (thin section, embedded grains or polished section).

The microchemical tests were selected from those given by Short, Chamot and Mason, and Feigl.[1] A few tests required modification, due in part to high percentages of iron and calcium present in many of the samples.

The procedure may seem unnecessarily extensive. It must be remembered, however, that the objective was to find out what

[1] Short, M. N.: Microscopic Determination of the Ore Minerals, U. S. Geol. Survey, Bull. 825, pp. 115–173, 1931. Chamot, E. M., and Mason, C. W.: Handbook of Chemical Microscopy, vol. II. New York, 1931. Feigl, Fritz: Qualitative Analyse mit Hilfe von Tüpfelreaktionen. Leipzig, 1931.

the variables are and how they vary for the known ore body. Some tests might be dispensed with after the type diagram is firmly established—with the danger that a variable of importance may be overlooked.

The preparation and testing of a single sample according to the scheme given below required about two hours, a large part of this time being used in preparation of the solution.

From each sample a definite small volume was treated with 1 : 1 hydrochloric acid in a small test tube. Two " ivory spoonfuls " (about 0.2 cc.) of powdered sample were usually sufficient. In some cases where the content of " insoluble " was very low and the carbonate content correspondingly high, a larger sample, less finely divided, was found more satisfactory. The gases liberated were noted. Carbon dioxide was detected by passing through barium hydroxide solution; hydrogen sulphide by its odor and by lead acetate paper. The approximate amounts were estimated, the " units " being *high, low, trace* and *not detected.*

After any violent effervescence of carbon dioxide had ceased, the solution and powder were boiled, with added acid if necessary, until most of the iron entered solution, as indicated by the powder, ordinarily more or less red, changing to white or colorless. The solution was filtered while still hot (so that calcium sulphate and lead chloride remain in solution), thus obtaining a clear solution and an insoluble residue.

The insoluble residue was first examined by immersing some of it in oils of known refractive index under a petrographic microscope. Bromoform was found to be a useful immersion medium; it served both as an index liquid and as a " heavy " liquid. Through its use barite, for example, was easily recognized in the presence of silica, and any undissolved iron oxide could be differentiated from the lighter carbonaceous residue.

Silica was recognized in the insoluble residue in three distinct forms; (1) euhedral quartz, (2) a micro-phase, or micro-form, (3) precipitated amorphous silica. The description and significance of each will be discussed later.

In some instances it was found necessary to treat either isolated

fragments of the insoluble residue, or aliquot parts, by various microchemical tests. Thus a black opaque grain, of unknown composition but suspected of being a sulphide, was removed to a clean glass slide and dissolved in a small drop of nitric acid, then tested by the potassium mercuric thiocyanate microchemical test for copper and zinc. It is well to remember that sulphides of groups I and II of the usual qualitative scheme, together with pyrite, are insoluble in hydrochloric acid. If white opaque grains were noted, some part of the insoluble residue was fused in a small soda bead, dissolved in a drop of hydrochloric acid on a small watch glass and the alizarin-S test used to show the approximate amount of aluminum, and the probable presence of an insoluble silicate. White opaque grains, which were heavier than bromoform, were recrystallized from concentrated sulphuric acid, thus quickly differentiating between barite, anglesite, anhydrite (some varieties of which were not readily soluble in HCl), and celestite.

The total amount of insoluble residue and the percentages of its various constituents were estimated for each sample.

The clear solution from the HCl treatment was concentrated to a definite volume, in order to allow estimates of the various constituents there present to be translated into the percentage present in the original sample. For two "ivory spoonfuls" of the original sample, concentration to one cubic centimeter was found convenient. Uniform-sized drops were used as "solution of unknown" in the microchemical tests.

Microchemical Tests.

Most of these tests, together with the necessary technique, are described by Short,[2] Chamot and Mason,[2] and Feigl.[2] In these works, however, the tests are generally listed under the ion tested for. Such a classification is somewhat unfortunate, as some of the tests serve to detect more than one element. Consequently, I have listed in Table I the single ions or groups of ions detected in the course of each test.

[2] *Op. cit.*

TABLE I.

Ions and Compounds.	Test.
Fe''	Potassium ferricyanide
$CaSO_4$, $PbCl_2$	Distilled water
Fe''', Cu, Zn, Co, (Ni)	Potassium mercuric thiocyanate
Pb, As, Cu, (Bi, Sb, Sn, Hg, Cd)	Potassium iodide-cæsium chloride
AsO_4, PO_4, SiO_3	Ammonium molybdate
Mn	Sodium bismuthate
Ca, Ba (Sr) Pb	Sulphuric acid
SO_4	Calcium acetate
Al	Alizarin
Mg	Quinalizarin
Mo	Zinc-ammonium thiocyanate
K	Chloroplatinic acid
Na	Zinc-uranyl-acetate

Ions enclosed in parentheses are those which were not found in this particular example, but which the tests would have detected.

Several improvements in the methods of applying these tests were discovered during the examination of these oxidized mineral deposits. The more important of these will be briefly noted.

Potassium Ferricyanide.—This test has been found useful to confirm the presence of zinc, in the absence of ferrous iron. It is especially useful in that ferric iron does not interfere.

Distilled Water.—A test drop, including a portion of any salt which may have separated on cooling the original solution, is evaporated to dryness on a glass slide, and a drop of distilled water added. The semi-soluble salts, particularly lead chloride and calcium sulphate, may crystallize out. The calcium sulphate crystallizes in the easily recognized form of gypsum. The addition of a small fragment of potassium iodide causes the replacement of lead chloride crystals, which somewhat resemble gypsum needles, by yellow lead iodide.

Potassium Mercuric Thiocyanate.—It has been found that the addition of a drop of 12 per cent. disodium phosphate reduces the intense red developed by high ferric iron content, without interfering with the reaction for other ions.

Potassium Iodide-Cæsium Chloride.—This useful test may be somewhat modified according to the principal elements tested for,

such as separating the nitric acid soluble portion from the nitric insoluble, and testing each portion after evaporation and resolution in 1 : 5 HCl. Further, the order of adding the reagents may be reversed (as when testing for antimony and/or bismuth). A convenient supplementary test to differentiate between antimony double iodide and bismuth double iodide is to add a fragment of sodium sulphide; antimony dissolves, bismuth does not.

Large amounts of iron give reactions with this test. These are best learned by the use of a "known solution" such as a drop of 20 per cent. ferric chloride solution (such as is used in etch test of mineralography). The troublesome free iodine may be sublimed off by gentle warming, without disturbing most of the other reactions.

Ammonium Molybdate.—The use of tartaric acid, as described by Feigl, serves to differentiate between phosphate and arsenate.

Calcium Acetate.—This test is only necessary where no excess calcium has been found by addition of sulphuric acid (1 per cent.).

Alizarin.—The use of filter-paper impregnated with ferrocyanide, as described by Feigl, is superior to the alizarin-S test, since it allows the detection of minute amounts of aluminum in the presence of large amounts of ferric iron.

Quinalizarin.—The sensitivity of this test is increased by the presence of calcium and other ions which form insoluble hydroxides on addition of sodium hydroxide. This is a disadvantage when estimates are desired of the amount of magnesium present.

Known Solutions.—A set of solutions of known strength was found necessary. These were used not only to study the reactions of different tests, but also for estimating the amount of elements and compounds present in the unknown solutions, by comparing the results produced by the known with those produced by the unknown solution. The known solutions were usually made to contain one per cent. of some soluble salt of the desired element. Thus, in one instance, the potassium mercuric thiocyanate test on a drop of unknown solution gave a crop of zinc mercuric thiocyanate crystals about twice as plentiful as the crop of crystals produced from a similar volume of a one-percent.

zinc acetate solution (nearly 0.3 per cent. in zinc)—the unknown solution contained 0.6 percent. zinc. Since the volume of the original unknown solution, of which the drop tested was an aliquot part, was approximately one cubic centimeter, and the volume of the sample used to make this solution was 0.2 cc. (2 "ivory spoonfuls"), the zinc content of the original sample was approximately 3 per cent. The absolute error is undoubtedly high, but the method is sufficiently accurate for the purpose of comparison between samples, especially if performed by the same observer.

Results of Tests.

The minerals, elements, and compounds found by testing the samples from the known ore body used as an example were:

	From Solution:	From Insoluble Residue:
H_2S	Fe″ and Fe‴	Euhedral quartz
CO_2	PO_4	Microsilica
	Mn	Precipitated silica
$CaSO_4$	Mg	Carbon and carbonaceous residue
Pb	Ca	Barite and barium sulphate
Ba	S and SO_4	Lead sulphate
Cu	Al	Anhydrite
Zn	SiO_2	Chalcocite
Co	Mo	Alumina
As	K	
	Na	

Of these, for this particular type of ore body, ferrous iron, barium, copper, cobalt, molybdenum, phosphate and manganese were present in relatively minute amounts. Manganese and phosphate appear to be very low throughout the Sierra Mojada district, and ferrous iron is far from plentiful. Elsewhere in the district, barium, copper, cobalt, and molybdenum, as well as strontium, are present in greater amount but are associated with somewhat different types of ore.

Silica.—Free silica occurred in the insoluble residue in three distinct forms: precipitated silica, euhedral quartz and a microphase, here termed microsilica. The precipitated silica is characterized by its low index (about 1.46) and isotropic character;

in the one instance found it resulted from boiling the solution to dryness after the formation of a gel; since the same sample gave a high percentage of zinc, it was probably due to the decomposition of calamine.

Euhedral quartz is used to designate quartz prisms terminated at each end by sharp-pointed pyramids. They were found to be surprisingly uniform in size, and, where no microsilica occurred, to be perfectly developed.

The term microsilica is applied to a micro-phase which has not been positively identified. Under the microscope this silica appears as a felted mass of minute (seldom over two microns) fibers and plates. The larger plates show a form of undulatory extinction somewhat suggestive of flamboyant quartz. Some areas appear isotropic, probably due to the minute size of the fibers or plates. The larger fibers are positively elongate. The aggregate index is above 1.540, but generally below 1.545. Thus, this mineral is not true chalcedony (chalcedonite) which has fibers of negative elongation, and indices about 1.537; nor is it all quartz, the lower index of which is 1.544. Possibly, it is quartzine,[3] which has been described as fibrous to platy, with fibers of positive elongation. It may also be closely related to the jasperoid that is composed of cryptocrystalline quartz, as described for many limestone districts.[4]

The microsilica commonly encloses quartz crystals. These resemble the euhedral quartz described above, except that the terminations are somewhat rounded as if by solution. These crystals, in contrast to the plates of microsilica, show no undulatory extinction.

The full explanation of the silica must await further research.

[3] Sosman, R. B.: The Properties of Silica, p. 154. New York, 1927. Michel-Lévy and Munier-Chalmas: Mémoire sur diverses affectées par le réseau élémentaire du quartz. Bull. Soc. Franc. Mineral. 15, pp. 166–174, 1892. Wetzel, W.: Untersuchung über das Verhältnis von Chalcedon und Quartzin zu Quartz, pp. 356–366. Centrbl. Min., 1913.

[4] Gilluly, James: Geol. and Ore Deposits of the Stockton and Farfield Quadrangles, Utah. U. S. Geol. Survey, Prof. Paper 173, pp. 97–101, 1932. Smith, W. S. T., and Siebenthal, C. E.: U. S. Geol. Atlas, Folio 148 (Joplin), pp. 13–19, 1907.

It is sufficient here to note that there are two distinct forms of silica, presumably introduced during silicification of the limestone. These forms are separable from the chert nodules of certain stratigraphic horizons in the district, which appear more closely related to the formation of the limestone and dolomite than the formation of the ore deposit.

Acid-Soluble Minerals.—Certain deductions may be drawn as to the minerals present in the samples from the elements and compounds found in the hydrochloric acid solution. Alumina together with silica would seem to indicate an acid-soluble aluminum silicate, possibly allophane. Hydrogen sulphide might be derived from a sulphide of a metal higher than Group II of the customary analytic scheme, possibly calcium sulphide, or from gas inclusions of calcite grains. Calcium sulphate, here often referred to as gypsum, was probably present in the sample as such; it entered the solution due to its greatly increased solubility in hot acid and in the presence of certain salts such as magnesium chloride; anhydrite is much less readily dissolved than gypsum, though its ultimate solubility may be the same. That gypsum was not derived from a reaction of calcite with other sulphates, such as jarosite, was demonstrated in one instance by leaching a powdered sample with hot water, from which gypsum recrystallized on cooling.

The Type Diagram.

In order to illustrate the distribution of the variations of the known ore body, graphs were plotted for each variable (Fig. 1). These graphs are placed under an outline of a vertical section through the drift that cuts the ore body. Thus the abcissæ of the graphs are based on the location of the samples with respect to the drift, and the ordinates show the relative amounts of each variable present. The scales of the ordinates have been varied so that the curves are approximately the same size; if the same scale were used throughout, the variations of the elements and compounds present in small amounts would be concealed.

Graphs are given only for those variables which showed significant and comparatively regular trends. These would be the

variables which offer most promise of indicating unknown ore bodies. Some that showed erratic trends were omitted, such as ferric iron; also, those that were present in too constant and small

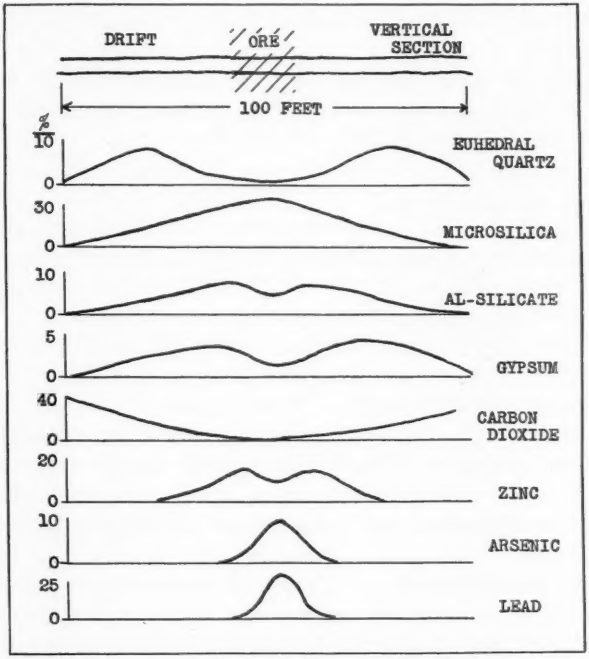

FIG. 1. Type diagram of zoning around oxidized silver-lead ore body, Sierra Mojada, Coahuila, Mexico.

amount to allow detection of variations, such as manganese. A greater number of samples might show iron to be a significant variable, but even a different technique of testing would be of doubtful value for manganese as long as it remains low and constant. However, the test for manganese should not be omitted: the time saved would be negligible, and an increase in manganese might indicate an important change in the deposit.

The scales shown in the figure are only approximate, and the graphs themselves are somewhat idealized. This was partly necessary, due to the small number (ten) of samples available. The method had not been conceived at the time the samples were taken; yet it was from the study of these samples that the method originated.

In practice more samples, carefully located, would be taken. Silver values would be shown by an additional graph, compiled from routine assays.

INTERPRETATION.

It is obvious that a part of the above described example of orebody zoning is due to secondary alteration, such as the distribution of the sulphate (gypsum) and of the zinc. On the other hand, the microsilica and euhedral quartz are apparently due to hypogene processes. Thus, the method here given is directly concerned with the present distribution and only indirectly with the causes of such distribution. However, the knowledge of the genesis of the various features may be important in interpretation and prediction. For instance, it was found that euhedral quartz was formed before the ore. There arises the possibility that euhedral quartz may occur due to a temporary period of deposition, without being followed by ore.

The gypsum here described is regarded as the result of oxidation of sulphide ore, and the reaction of the sulphate solutions with limestone. But syngenetic gypsum may occur in a limestone formation; such gypsum combined with gypsum from the oxidation of ore might result in an atypical trend in its variation curve.

These instances show that a knowledge of the genesis of the deposit may indicate caution in interpretation, or explain certain irregularities encountered. The interpretation is benefited accordingly. Since the method does not depend on a single variation, but rather on multiple variations, any lack of knowledge as to genesis does not tend to introduce complications.

Differences in the mode of genesis of the variables is a fortunate feature, since it reduces the possibility that a zoning as a

whole might be reversed. Thus, it is difficult to conceive that zoning of microsilica, euhedral quartz, and gypsum around an ore body should all show variations the reverse of those shown in the type diagram. If one variant, possibly due to a different genesis, appears out of step, the remainder would be sufficient for a decision as to the location of the ore. This is essentially a method of multiple facts—not multiple hypotheses.

SOME APPLICATIONS.

The application of the type diagram to the finding of ore in workings and bore-holes is evident from the type diagram, which shows that increases of euhedral quartz, gypsum, microsilica and aluminum silicate are signboards, pointing to the ore. The use of the method for diamond-drill holes should be especially valuable. A diamond-drill hole is almost one-dimensional. All possible information that the cores can furnish as to conditions normal to its trend must be utilized to obtain the maximum efficiency from this method of prospecting. The methods described in this article indicate a manner of studying cores.

A knowledge of ore-body zoning may be useful in locating ore beyond a fault. Suppose that an ore body has been displaced by a fault, and that beyond this fault some euhedral quartz and gypsum were detected in the limestone. Further, that cross-cutting in one direction showed an increase of gypsum and an increase of microsilica at the expense of euhedral quartz. The inference, from a study of the type diagram, would be that the faulted segment of ore lay ahead of this cross-cut. Caution is necessary in that solutions moving along the fault may have introduced some of the variables of the ore-body zoning. Further, slivers within a fault zone may have moved in an opposite direction from that taken by the faulted segment proper.

Although most of this article has dealt with the variations of the outer zone, or auriole, around ore bodies, there may conceivably be instances where variations within an ore body are important, such as in locating ore shoots within an ore body, and showing when the center of an ore shoot is reached.

Doubtless other instances of ore-body zoning and other possible applications will occur to the reader. If so, the literature of economic geology is far from overburdened with such descriptions and discussions. There seems here an open field for the company geologist, who has the best opportunity for the necessary observations.

ACKNOWLEDGMENTS.

This paper is a by-product of the results accomplished under a grant of the S. F. Emmons Memorial Fellowship in Economic Geology, to the directors of which the writer wishes to acknowledge his indebtedness. The writer wishes to express his sincere thanks to the officials of the Cia. Minera de Peñoles and to Mr. Van Dyne Howbert for their generous assistance, and to the Peñoles staff at Sierra Mojada for their generous hospitality and aid during the fieldwork. The writer is greatly indebted to Professor Alan M. Bateman for his helpful suggestions at all stages of the research and in the preparation of this paper.

LABORATORY OF ECONOMIC GEOLOGY,
YALE UNIVERSITY,
NEW HAVEN, CONN.,
July 2, 1935.

HYDROTHERMAL EXPERIMENTS WITH LEAD AND ZINC MINERALS.

O. H. KRISTOFFERSON.

INTRODUCTION AND ACKNOWLEDGMENTS.

OBSERVATIONS have shown that galena and sphalerite are deposited at temperatures below 500° C. at certain fumaroles in the Valley of Ten Thousand Smokes,[1] in the Katmai region, Alaska. Zies says:

> A magnetite deposit existed at fumarole No. 148 in 1919. In 1923 C. N. Fenner . . . did not find any magnetite . . . and the temperature of the steam was 97° C. . . . The incrustations that Fenner brought back from this area proved to be siliceous material on which well developed crystals of galena, sphalerite and the sulphides of copper were formed.

Fenner [2] quotes Lindgren as follows:

> With lowering pressure and congealing of the non-volatile material the volatile compounds tend to escape. . . . When magmas consolidate, these constituents are expelled . . . they (particularly the halogens) carry with them many heavy metals like iron, copper, zinc, lead, or tin, because volatile compounds are formed.

Volatility is an important contributing factor in the formation of ore deposits, for it provides a medium by which the metals may be carried out from the magma into the surrounding rock.

Vapor pressure, critical temperature, partial pressure and concentration of the respective compounds are the chief factors that control the volatile phase of ore deposition.

The present paper deals with an investigation of the extent to which the chlorides of lead and zinc may be transported in the

[1] Zies, E. G.: The Valley of Ten Thousand Smokes, I. The Fumarolic Incrustations and their Bearing on Ore Deposition. Nat. Geog. Soc., vol. 1, Katmai Series 4, p. 18, 1929.

[2] Fenner, C. N., Pneumatolytic Processes in the Formation of Minerals and Ores. Amer. Inst. Min. and Met. Eng., Lindgren Volume, p. 61, 1933.

vapor phase in the presence of steam and HCl vapor at temperatures below 500° C.

The writer is especially indebted to Dr. J. W. Gruner, who proposed the problem, and whose counsel has been of great value throughout this work. Dr. R. B. Ellestad, chemist of the Rockefeller Foundation National Laboratory for Rock Analysis, University of Minnesota, and Dr. M. H. Froberg, have offered valuable and helpful suggestions. Dr. A. Helke, of Freiberg, kindly furnished a specimen of christophite. The writer is also indebted to the New Jersey Zinc Company, Franklin, New Jersey, and the Empire Zinc Company, Hanover, New Mexico, for selected specimens of sphalerite generously furnished by them.

REVIEW OF LITERATURE.

There is no work known to the writer that describes experiments on the volatility of lead and zinc chlorides in the presence of steam and HCl vapor at temperatures below 500° C. Some experimental work has been done on the volatility of lead and zinc chlorides at higher temperatures. Eastman and Duschak [3] conducted experiments on the vapor pressure of lead chloride at temperatures between 500° and 800° C. The melting point of lead chloride was determined as 495° C. and the boiling point as 945° C. at a pressure of 754 mm. of Hg. The average melting point of 498° C. was adopted as the best of all determinations.

Maier [4] did extensive work on the vapor pressures of the common metallic chlorides in the dry state at high temperatures. Some of these are shown in Fig. 3.

Zies [5] estimates the tremendous volume of volatiles given off by the fumaroles in the Valley of Ten Thousand Smokes, and emphasizes the transportation of metals in the vapor phase as metallic halides. He likewise shows the various stages in the deposition of the incrustations and the changes which take place as the temperature at the different vents is lowered. He also

[3] Eastman, E. D., and Duschak, L. H.: U. S. Bur. Mines, Tech. Paper 225, 1919.

[4] Maier, C. G.: Vapor Pressures of the Common Metallic Chlorides and a Static Method for High Temperatures. U. S. Bur. Mines, Tech. Paper 360, 1925.

[5] Zies, E. G.: *Op. cit.*, p. 4.

gives a clear account of the formation of the magnetite, which, being unstable in the changing environment as the temperature is lowered, gives way to the sulphides of copper, lead and zinc.

Fenner,[6] in a recent paper, stresses the fact that "agents best adapted to effect a primary separation of material from the magma and transport it outward into the surrounding rocks are the gaseous emanations."

To quote further:

> Certain volatiles are peculiarly adapted to serve as agents of selective collection, transportation, and redeposition of the metallic constituents of the magma. Under favorable circumstances small concentrations of metallic elements originally distributed through a mass of magma may thus be collected into large bodies of ore.
>
> Because of the volatility of chlorides, and because direct observation of volcanic sublimates shows their presence, it is deemed probable that chlorides are the most important form of combination in which metals are sublimed from the magma; fluorides to a somewhat less degree. The high vapor pressure of the chlorides of some of the most common metals Zn, Cd, Pb, Ni, Sn, As, Sb, Bi, should be noted. $FeCl_3$ and $AlCl_3$ are among the highest, and because of this and because of the mass action effect caused by their large concentration in the magma, they might be expected to be volatilized in the greatest quantities.

Weed,[7] in a summary statement, says:

> The magma is the vehicle, the volatiles the motive force during the entire process of igneous intrusion, differentiation and ore genesis.

Clark,[8] in accordance with these views, states:

> In ore formation the magmatic chlorides and fluorides probably have definite functions. In the molten rock they convert some part of the heavy metals into compounds which are volatile at high temperatures, and which tend to gather at the margins of intrusives.

Grout's[9] views are as follows:

> Some heavy metals such as form ores at depth are detected at fumaroles. The halogen compounds of many metals can be carried as gas or in

[6] Fenner, C. N.: *Op. cit.*, pp. 58–106.

[7] Weed, W. H.: The Rôle of Volatiles in Ore Genesis. Amer. Inst. Min. and Met. Eng., Feb., 1933. (Photostatic copy.)

[8] Clark, F. W.: U. S. Geol. Surv. Bull. 695, p. 630, 1920.

[9] Grout, F. F.: Petrography and Petrology, pp. 219–220, 1932.

liquid solutions, either alkaline or acid. It should be added that the emanations may be so hot as to be dissociated and perhaps neither acid nor alkaline. The formation of sulphides may be a late reaction during cooling rather than a precipitation from a hot alkaline liquid.

EXPERIMENTAL WORK.

Description of Apparatus.

The apparatus used in the experiments consisted of: (1) the electric tube furnace,[10] (2) pyrex-glass tube with a valve.[11] A few minor changes were made on the tube furnace, namely, the addition of a ground-glass stopper and a coil condenser.

The furnace temperature was regulated by a Leeds-Northrup indicating controller potentiometer system, which maintained an accuracy of $5° \pm$ throughout the experiments.

The acid bottles contained hydrochloric acid of constant concentration (20 per cent. HCl), and boiling was continuous throughout an experiment. The acid in the refill flask was boiled for at least three minutes before it was siphoned into the main flask.

The mineral being treated was weighed in a glazed porcelain boat and placed in the furnace, after the required temperature had been reached, and the acid had been boiling for at least fifteen minutes.

In the experiments using the pyrex-glass tubes, the air was displaced by carbon dioxide before sealing.

Minerals and Synthetic Materials Used.

Since there are so many varieties of sphalerite, it was decided to carry out experiments on a number of different specimens. The following is a list of minerals and materials used in the experiments:

[10] Park, C. F.: Hydrothermal Experiments with Copper Compounds. ECON. GEOL., vol. 26, p. 859, 1931.

[11] Foreman, F.: Solubility, Hydrolysis, and Oxidation of Iron and Copper Sulphates. ECON. GEOL., vol. 24, p. 811, 1929.

I. Zinc sulphide—prepared.
II. Sphalerite—Franklin Furnace, New Jersey.
III. Sphalerite—Joplin, Missouri.
IV. Sphalerite—" Marmatite," Cleveland Mine, New Mexico.
V. Sphalerite—" Christophite," St. Christoph, Saxony.
VI. Lead chloride (C. P.).
VII. Galena—Yellowstone, Wisconsin.

The following determinations have been made by the writer:

	II.	III.	IV.	V.
Fe	Tr.	0.26	13.32	16.26
Mn			6.10	
Residue			1.64	3.86

In determining the iron content of sphalerites II and III, the iron was precipitated as $Fe(OH)_3$. In IV and V the iron was determined potentiometrically. The manganese was determined by the bismuthate method. The residue includes all the minerals that do not dissolve in dilute hydrochloric acid on gentle heating.

White zinc sulphide powder was prepared for preliminary experiments; 30 grams of zinc sulphate was dissolved in 200 cc. of water, and 5 grams of sodium acetate added at intervals. Hydrogen sulphide was allowed to bubble through the solution. The sodium acetate converts the sulphuric acid into acetic acid, thereby weakening the acidity of the solution. Otherwise, were the sulphuric acid allowed to accumulate, the reaction would stop.

The white sphalerite from Franklin Furnace, New Jersey, occurs associated with troostite and a black mineral which resembles franklinite. The sphalerite is pearly white to colorless, and contains many small inclusions of the black mineral. On analysis, the sphalerite showed a trace of iron, but this may have been due to the presence of the minute inclusions.

The Joplin sphalerite is yellow to brown in color. Associated with it are galena, marcasite, pyrite, chalcopyrite, chert, calcite, aragonite and quartz.

The " marmatite " variety of sphalerite is dark brown to black in color. Associated with it are pyrite, chalcopyrite, pyrrhotite, and calcite.

The "christophite" is black in color. Associated with it are quartz, pyrite and chalcopyrite.

The lead chloride (C. P.) was tested for impurities. Five grams were dissolved in 200 cc. of water and no residue remained, showing the absence of any sulphate. Neither copper nor iron were present, since a potassium ferrocyanide solution when added failed to show any brown or blue color.

The galena used was a specimen in the Mineralogical Collection at the University of Minnesota, from Yellowstone, Wisconsin.

Because of the difficulty of handling zinc chloride, it could not be used. It is next to impossible to work with the anhydrous chloride because it absorbs water so fast that it cannot be weighed accurately. If zinc chloride had been used, the slight alterations effected in the furnace, together with the small samples used, would have involved a large error.

Sphalerite decrepitates upon heating, even upon gradual heating. Since considerable error can arise by material jumping out of the boat, it was found advisable to use a specially constructed guard tube (pyrex glass) so that the material could again be collected in the event that decrepitation occurred.

All the varieties of sphalerite were given the following preliminary treatment. The sphalerite was crushed to about 1/16 inch size. This was hand-sorted under the binoculars, and only the material free from inclusions of pyrite, marcasite, chalcopyrite, etc., was used. This was heated to low redness in a stream of carbon dioxide for three minutes, and allowed to cool in carbon dioxide. Assuming that all the strain that exists within the crystalline material was relieved, the sphalerite was next digested in warm, very dilute HCl to eliminate any carbonate that might have been present. The material was washed repeatedly in hot water, until the water showed no trace of chloride in a test with silver nitrate. The heat treatment was applied again, but with no evidence of decrepitation.

Galena was given a similar treatment before it was used.

Preliminary Experiments with Sphalerite and Artificial Zinc Sulphide.

A series of trial experiments, mostly qualitative, were attempted in an effort to understand the various reactions of zinc sulphide at temperatures below 500° C.

1. In the tube furnace at 320° C., steam was passed over a boat containing Joplin sphalerite. The outgoing steam was tested for hydrogen sulphide and it was found that lead acetate paper became slightly coated with PbS. There were two possibilities as to the source of the hydrogen sulphide—the decomposition of the zinc sulphide, or the decomposition of possible submicroscopic pyrite or marcasite inclusions.

2. In an effort to get pure zinc sulphide, it was prepared artificially, as previously described. At a temperature of 335° C., steam was passed over a boat containing prepared zinc sulphide. Tests like those made before showed that hydrogen sulphide was given off.

Some of this pure zinc sulphide was then heated to 200° C. in a pyrex-glass tube containing a valve, in the presence of carbon dioxide. At the end of 12 hours the acetate paper test showed that some H_2S was still being given off.

There was a possibility that the H_2S given off was some of the original H_2S occluded in the zinc-sulphide precipitate, and not due to any breakdown of the zinc sulphide, as was previously supposed. To make sure of this, some zinc sulphide was heated to low redness in a glass tube in a stream of nitrogen. The gas was allowed to bubble into lead-acetate solution and a heavy precipitate of lead sulphide was formed. This proved that this artificial material contained adsorbed H_2S and could not be used for experimental work of this nature.

3. Acid vapor, consisting of steam and 20 per cent HCl, was passed over Joplin sphalerite in the tube furnace at 200° C. (About 3 liters of hydrochloric acid was used every 24 hours.) No noticeable change had taken place after three days.

4. This experiment was repeated at 230° C. with the same negative results.

It is interesting to note the behavior of sphalerite in the acid vapor in contrast to that of pyrite. Pyrite is decomposed by the acid vapor but not in a cold dilute HCl solution, whereas pure sphalerite is attacked in cold dilute HCl solution, but not by the acid vapor, that is, for temperatures below 290° C.

5. Experiment No. 4 was repeated at 460° C. for 31 hours. When the furnace was opened none of the sphalerite remained. The zinc sulphide had been converted to zinc chloride, which therefore is volatile at 460° C., and was carried out with the stream of acid vapor. $ZnS + 2HCl \rightarrow ZnCl_2 + H_2S$.

6. The same experiment was repeated using two boats, one in the front end of the furnace and one in the middle. In the front end, where the in-coming acid vapor was cooler, the sphalerite showed very little evidence of being attacked. On smooth cleavage surfaces, small pits or centers of solution were beginning to form, although no definite etch pattern was evident. The sphalerite in the center of the tube showed marked attack, especially along cleavage planes. Just why the alteration should proceed so quickly and deeply along cleavage planes and leave the portion adjacent only slightly affected, is difficult to explain, unless there was submicroscopic fracturing, and these cracks offered easy access to the action of the hot gases.

There were drops of moisture within the tube furnace after cooling, which in a blowpipe flame gave an apple-green color with cobalt nitrate solution, a very sensitive test for zinc. These droplets were hydrous zinc chloride, which had been deposited as a sublimation product on the walls of the tube near the outlet.

Steam was passed over the different varieties of sphalerite in the tube furnace at temperatures ranging from 200° to 500° C., but no alterations were noted.

Further Experiments with Sphalerite in Acid Vapor.

These experiments on sphalerite were conducted in an electric tube furnace in an acid-vapor dynamic system.

A half-gram sample of Joplin sphalerite was weighed out in a porcelain boat, and placed in the furnace after the required

temperature of 250° C. had been reached. The experiment was allowed to run for 90 hours. When it was finished, the acid vapor was shut off first in order that there might be no acid fumes left when the furnace had cooled. This would prevent any zinc chloride from condensing on the boat, thereby increasing its weight and introducing an error.

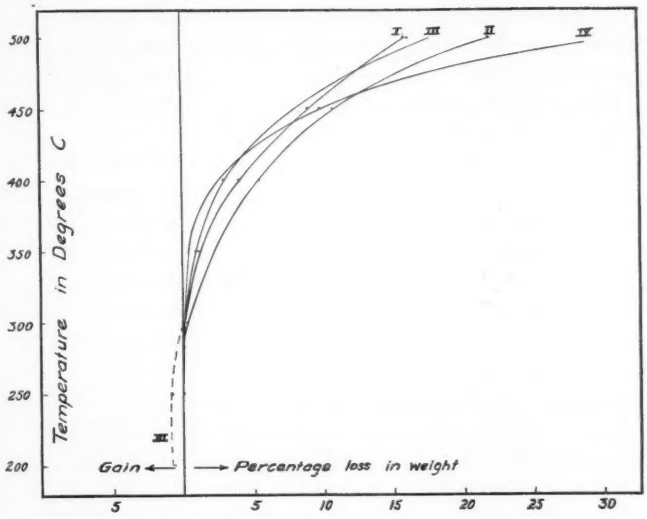

FIG. 1. Curves for the decomposition and volatilization of sphalerite in aqueous HCl vapor. I. Pure sphalerite, II. Joplin sphalerite, III. Marmatite, IV. Christophite.

The boat was placed in an oven and heated to 120° C. for three hours, cooled, and weighed. The experiment was repeated at temperatures of 300°, 350°, 400°, 450°, and 500° C. The results are tabulated in Table 1. The length of an experiment ranged from 35 to 94 hours, and the results were calculated to 40 hours.

A series of similar experiments were made with Franklin Furnace sphalerite, the results appearing in Table 2.

The results of the experiments conducted on "marmatite" appear in Table 3. The accuracy of the results on this variety is somewhat doubtful on account of the complexity of the specimen. For instance, the iron content of the cleaned sphalerite was determined as 13.32 per cent. There must have been, however, some small pyrrhotite inclusions in the sphalerite grains, since in the preliminary treatment of the ore some grains of pyrrhotite were removed with a magnetized needle under the binoculars. Examination of this specimen in polished section showed the presence of pyrite, chalcopyrite and calcite, but no pyrrhotite.

From Fig. 1, it is evident that the marmatite had been attacked below the temperature at which zinc chloride becomes volatile. There was an increase in weight of the samples below 290° C., due to the formation and accumulation of zinc chloride. Also there was the possibility of the formation of manganous chloride, cadmium chloride, and ferrous chloride, which have low vapor pressures below 300° C. (Fig. 3). Ferrous chloride is formed according to the following equation:

$$FeS + 2HCl \rightarrow FeCl_2 + H_2S.$$

Zies [12] says that ferrous chloride in the presence of steam probably gives FeO. Since there was hematite left in the boat, $FeCl_3$ must have been present, and the following equation may possibly have taken place:

$$2FeCl_2 + 2HCl \rightarrow 2FeCl_3 + H_2.$$

This is theoretically possible, since the H_2 would be removed as fast as it was formed. However, there is a possibility that there may have been some oxidation of the ferrous iron to ferric iron by a partial breakdown of the steam, or by some oxygen getting into the apparatus. Ferric chloride exerts a high vapor pressure below 300° C., but in the presence of steam some of the ferric chloride is converted to hematite.[13] Zies says:

> If the partial pressure of the HCl is low and the temperature is low,

[12] *Op. cit.*, p. 8.

[13] *Idem*, p. 9.

relatively little ferric chloride will be removed and that which is transported is likely to be promptly hydrolyzed to form hematite:

$$Fe_2Cl_6 + 3H_2O \rightleftarrows Fe_2O_3 + 6HCl.$$

. . . HCl is again liberated and this can again react with the iron-bearing minerals over which it is then sweeping in the following manner:

$$Fe_2O_3 + 6HCl + H_2O \rightleftarrows Fe_2Cl_6 + 4H_2O.$$

This was verified by the fact that the amount of hematite remaining in the boat at the completion of an experiment increased as the temperature increased.

The results of the experiments with "christophite," appear in Table 4. Like marmatite, the christophite, due to its complex nature, introduces many difficulties. Reh [14] states that the christophite contains ex-solution particles of pyrrhotite, cubanite, a cubanite-like mineral, and chalcopyrite. Associated with it are quartz, pyrite, cassiterite, löllingite and arsenopyrite. Examination of the single specimen available in polished section showed the presence of only quartz, pyrite, and chalcopyrite as inclusions.

As in the experiments on marmatite, there was some volatilization of $FeCl_3$ with the $ZnCl_2$, and also subsequent formation of hematite.[15] The quantity of hematite increased as the temperature increased.

In the experiment on christophite at 250° C., the contents of the boat showed an insignificant loss (0.0005 g.). After the experiment, the material remaining in the boat was thoroughly washed in hot water, and 0.0049 g. of zinc chloride was dissolved out. Had there been no volatilization of $FeCl_3$, the boat should have shown a gain in weight of 0.0034 g. Since $ZnCl_2$ had not

[14] Reh, H.: Beitrage zur Kenntnis der erzgebirgischen Erzlager. Neues Jahrb. für Min., Beil. Bd. 65, Abt. A., p. 36, 1932.

[15] The volatilization of $FeCl_3$ was vividly demonstrated during the experiment conducted at 300° C. At this temperature volatilization was small. However, one of the rubber tubes of the acid bottle became so badly decomposed that some of the acid vapor escaped into the room. The portion of the acid vapor which passed through the furnace was not enough to carry away the reaction products, and beautiful hematite-coated crystals of zinc chloride were deposited on the boat and on the interior of the guard tube. In the other experiments there was enough water vapor present to cause most of the $FeCl_3$ to be changed to Fe_2O_3 and left behind in the boat, and that which volatilized was immediately swept out of the furnace.

Table 1. Dynamic experiments with brown sphalerite (Joplin) in aqueous HCl vapor.

Temp. °C.	Grams ZnS	Hours	Grams lost	Calc'd. 40 hrs.	% Change
250	0.4540	90.0	None	----	----
300	0.4403	90.0	0.0048	0.0021	0.47
350	0.4093	94.5	0.0359	0.0151	3.68
400	0.5007	45.0	0.0317	0.0281	5.61
450	0.5030	47.6	0.0707	0.0549	10.91
500	0.4222	91.5	0.2143	0.0936	22.16

Table 2. Dynamic experiments with colorless sphalerite (Franklin Furnace) in aqueous HCl vapor.

Temp. °C.	Grams ZnS	Hours	Grams lost	Calc'd. 40 hrs.	% Change
275	0.5051	46.0	0.0004	----	----
300	0.9087	61.5	0.0009	0.0005	0.06
350	1.0035	46.5	0.0135	0.0116	1.15
400	1.0100	44.5	0.0468	0.0420	4.15
450	1.0283	36.0	0.0842	0.0935	9.09
500	1.0011	37.1	0.1479	0.1594	15.92

Table 3. Dynamic experiments with black sphalerite (marmatite) in aqueous HCl vapor.

Temp. °C.	Grams ZnS	Hours	Grams gained or lost	Calc'd. 40 hrs.	% Change
200	1.0021	43.2	0.0078	0.0072	0.71
250	1.0004	29.3	0.0058	0.0078	0.77
300	1.0096	40.3	-0.0016	-0.0015	- 0.15
350	1.0003	42.5	-0.0121	-0.0113	- 1.13
400	1.0088	39.2	-0.0308	-0.0313	- 3.10
450	1.0026	40.0	-0.1003	-0.1003	-10.00
500	1.0135	45.6	-0.1879	-0.1648	-16.26

Table 4. Dynamic experiments with black sphalerite (christophite) in aqueous HCl vapor.

Temp. °C.	Grams ZnS	Hours	Grams lost	Calc'd. 40 hrs.	% Change
250	1.6752	44.5	0.0005	0.0005	0.03
300	2.4342	46.5	0.0062	0.0053	0.21
350	2.6201	46.0	0.0124	0.0107	0.40
400	2.5653	24.0	0.0270	0.0450	1.75
450	2.0502	39.3	0.2910	0.2960	14.43
500	1.6537	44.0	0.4807	0.4370	26.40

Table 5. Dynamic experiments with galena in steam.

Temp. °C.	Grams PbS	Hours	Grams lost	Tarnish
250	2.0192	60.3	0	Dull surfaces
300	2.0016	64.5	0	Light purple
350	2.0106	64.7	0	Purple
400	2.0114	69.0	0	Deep purple
450	2.0201	62.3	- 0.0003	Purplish blue
500	2.0737	72.0	- 0.0002	Dull bluish gray

Table 6. Dynamic experiments with galena in aqueous HCl vapor.

Temp. °C.	Grams PbS	Hours	Grams gained or lost	Calc'd. 50 hrs.	% Change
200	2.0081	56.5	0.0036	0.0031	0.15 x
250	2.0040	60.2	0.0084	0.0069	0.34 x
300	2.0175	68.9	0.0166	0.0120	0.82
350	2.0292	62.0	0.0429	0.0346	1.70
400	2.0108	72.0	0.1032	0.0716	3.56
450	2.0106	39.5	0.0881	0.1115	5.54
475	2.0309	89.5	0.0138	0.0077	0.38
500	2.0189	48.0	- 0.1210	- 0.1260	- 6.24

x The normal speed of reaction is not reached below the temperature at which lead chloride is volatile, since the lead chloride forms a protective coating on the galena, and the alteration will not be uniform over a given period of time.

Table 7. Dynamic experiments on the volatility of lead chloride (C.P.) in aqueous HCl vapor.

Temp. °C.	Grams $PbCl_2$	Hours	Grams lost	Calc'd. 50 hrs.	% Change
150	1.0444	42.7	None	----	----
200	1.2376	46.0	None	----	----
250	1.0034	38.7	None	----	----
300	1.0106	56.0	0.0004	0.0003	----
350	1.0014	39.0	0.0032	0.0040	0.41
400	1.0018	40.2	0.0165	0.0204	2.03
450	1.1158	30.3	0.0665	0.1095	9.81
500	1.1052	27.6	0.4471	0.8095	73.24

shown much volatility below 290° C., and since there was an actual loss observed, it can be assumed that this was due to the volatility of $FeCl_3$. This is contrary to the result of the experiment on marmatite, which at 250° C., showed a gain (Curve III, Fig. 1).

Discussion.—Zies[16] states that zinc chloride melts at 290° C., and has an appreciable vapor pressure even below its melting point. In the experiments on pure sphalerite, however, no volatilization of zinc chloride was detected below 290° C. In fact this holds for all the varieties of sphalerite investigated.

It will be noted in Tables 1 to 4 that the zinc of the sphalerite becomes volatile as $ZnCl_2$ at 290° C. It was at first thought that below 290° C., the acid vapor was non-ionized.[17] However, metallic zinc is attacked by the acid vapor at 200° C. As is seen, in the sphalerite high in iron there was some attack below 290° C. These alterations to zinc chloride below 290° C. may have been due to the possibility that the surfaces of the sphalerite and the metallic zinc adsorbed enough acid vapor so that the HCl would then act as an ionized solution. This does not explain why there was no alteration of pure sphalerite below 290° C. It is possible that the presence of isomorphous iron weakens the structure of the sphalerite to such an extent that the iron-rich varieties will be more readily decomposed by HCl.

Experiments with Galena.

The specimen of galena used in the experiments was a large crystal from Yellowstone, Wisconsin.

The galena was given the same preliminary heat treatment as the sphalerite to prevent any possible decrepitation, since, according to Buerger,[18] the galena from the Mississippi Valley commonly contains negative crystal cavities filled with sodium-chloride solution. No decrepitation occurred during the heating

[16] *Op. cit.*, p. 13.

[17] The dissociation of HCl, as given by L. Löwenstein, is 0.274 per cent at 1537° C Zeit. für physikalische Chemie, 54, p. 726, 1905.

[18] Buerger, M. J.: The Negative Cavities of Certain Galena and their Brine Content. Amer. Miner., vol. 17, pp. 228–233, 1932.

or during the experiments, and there was no evidence that this galena contained any of the mentioned cavities.

Steam was passed over galena in the tube furnace at temperatures ranging from 250° to 500° C. The results appear in Table 5. No changes in weight were noticed which were not within the limit of error. The galena tarnished very readily above 300° C., due to the formation of an oxide. Which oxide was formed is difficult to say. The oxide minerals of lead, minium ($2PbO.PbO_2$), massicot (PbO), and plattnerite (PbO_2) are of rare occurrence. They occur in the oxidized zones of lead deposits and are not known as primary minerals. Although it is not probable, there is a possibility that some of these oxides could have formed at high temperatures.

HCl acid vapor was passed over galena in the tube furnace at temperatures ranging from 200° to 500° C. The results appear in Table 6. From the results plotted in curve I, Fig. 2, it is

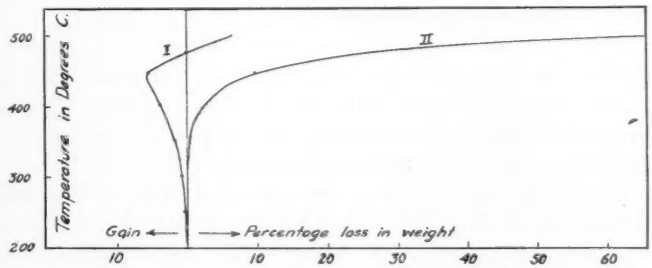

FIG. 2. I. Curve for the decomposition and volatilization of galena in aqueous HCl vapor. II. Curve for volatilization of lead chloride (C. P.) in aqueous HCl vapor.

evident that up to 450° C., lead chloride accumulates, but does not exert enough vapor pressure to be carried away as fast as it is formed. $PbS + 2HCl \rightarrow PbCl_2 + H_2S$. The curve shows the progressive gain in weight of the contents of the boat in the experiments up to 450° C. At this temperature there was a maximum amount of $PbCl_2$ formed over that which was volatilized.

At 475° C., the amount of $PbCl_2$ that volatilized almost equalled the increase in weight caused by the formation of the $PbCl_2$. Above 475° C., the amount of $PbCl_2$ that volatilized increased rapidly.

The first noticeable effect of alteration was observed at 250° C., when after 56 hours in the furnace, the galena was coated with numerous acicular crystals of lead chloride (synthetic cotunnite). At places an oriented growth of the crystals was noted. The best development of this orientation of the $PbCl_2$ crystals was noted at 300° C. As the temperature increased the cleavage surfaces of the galena became coated more and more until the surface was a dull semitranslucent mass of lead chloride with no individual crystals in evidence. At 450° and 500° C., what remained in the boat was a fused mass of lead chloride, and at the latter temperature intumescence occurred, showing that the lead chloride was in a viscous condition. When cooled, this fused mass was broken open, and there remained a few fragments of galena that had not altered to lead chloride.

Lead Chloride in Acid Vapor.—For comparison, a series of experiments were conducted with chemically pure lead chloride. These were made in the tube furnace, first in the presence of steam, with only negative results (200° to 500° C.), and then in acid vapor, the results appearing in Table 7.

Discussion.—It is evident from curve II, Fig. 2, that lead chloride exerts very little vapor pressure below 300° C. It is interesting that considerable lead chloride volatilized below its melting point, 498° C., while no volatilization of zinc chloride was observed below its melting point. As soon as the melting point was reached, however, the vapor pressure increased to such an extent that the volatilization could be measured.

From the comparative vapor pressure curves in Fig. 3, it would seem that very little vapor pressure would be exerted by lead chloride at 500° C., and by zinc chloride at 400° C. Still, in the experiments it was found that there was considerable volatilization at lower temperatures. This is no doubt due to the fact that the chlorides are swept out of the furnace as fast as they are

formed, provided the temperature is that at which they are volatile. Extended over a long enough period, the cumulative results are measurable.

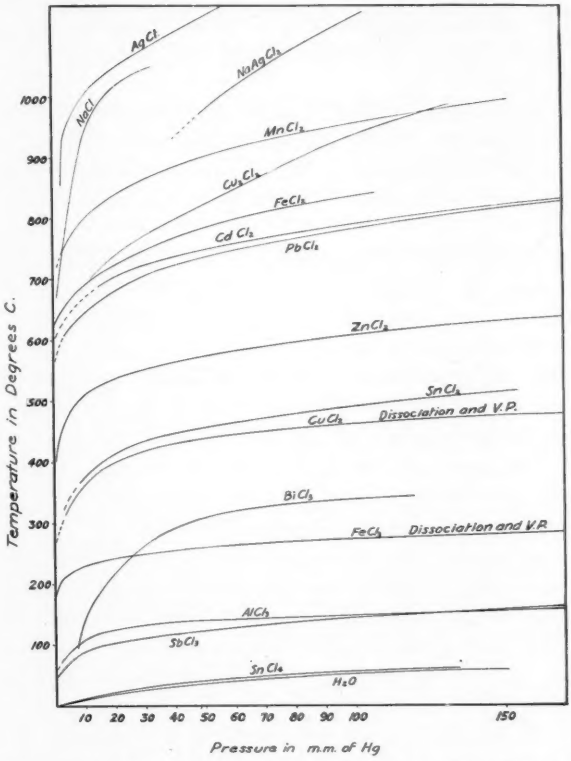

FIG. 3. Vapor pressure curves of the common metallic chlorides. (After Maier.)

DISCUSSION.

Lead and zinc sulphides occur in every type of deposit, from traces in magmatic segregation and pegmatites, through contact-metamorphic deposits, the different types of veins, and cold-water deposits.

It is reasonable to suppose that the hypogene lead and zinc deposits are formed at moderate to high temperatures, and at a depth where there is considerable pressure. Some of the largest deposits, Broken Hill, New South Wales, and the Sullivan Mine, British Columbia, appear to be of pneumatolytic or contact origin. The deposits at St. Christoph, Saxony, are in part, of pneumatolytic origin.

The environment in which it seems most logical that the deposition of metals like Pb and Zn should take place from the vapor state, would be conditions of high temperature due to intrusions near the surface where the rocks are highly fractured clear to the surface.

The results of the experiments show that lead and zinc may be transported as volatile chlorides above 300° C. Cotunnite ($PbCl_2$) has been found in volcanoes, but is rare, since it is very soluble in hot water.

As has been mentioned earlier in this paper, the sulphides of lead and zinc are deposited at fumaroles in the Katmai region, Alaska, at temperatures low enough to permit the existence of H_2S. The gases had free access to the surface and the temperature was probably below 400° C., since H_2S would be dissociated above that temperature, at atmospheric pressure.

A chart of the vapor-pressure curves of the common metallic chlorides (Fig. 3) shows that the metals are not deposited in any order directly dependent upon their vapor pressures. There are a few observations, however, that are striking. The chlorides of Mn, Cd, and Ag exert very little vapor pressure at temperatures below 600° C., and are the metals that form ores nearer to the surface than copper and tin, whose chlorides exert high vapor pressures at much lower temperatures. Lead and zinc are intermediate between these. Since $SnCl_4$ exerts such a high vapor pressure at lower temperatures, it would be especially active above 318° C., its critical temperature, but since it is so readily hydrolyzed, it is never found to have migrated far from the parent magma. As the temperature rises, the vapor pressure of the common metallic chlorides increases in the following order:

Sn, Cu, Pb, Zn, Mn, Ag,—and in the zonal arrangement of the metals Sn is found nearer the intrusive, while Ag, which exerts the least vapor pressure, is found farthest away. This is the exact reversal of what would be expected were the zones determined by vapor pressures. Where there are clear zones developed, therefore, other factors enter, which change the order of deposition.

It is a conspicuous fact that the greatest percentage of the zinc deposits of the world are mesothermal. It is the belief of the writer that, during ore formation in the mesothermal zone, both liquids and gases are in contact with each other, as has been indicated by Lindgren,[19] where he states that the deposits of the mesothermal group were probably formed under a cover of from 4000 to 12,000 feet.

Fenner [20] states:

> It might be thought that the pressure to which the emanations are subjected, because of the difficulty of escape, would cause their condensation to the liquid form. This is hardly possible unless the pressure is so great as to prevent completely the separation of emanations from the magma, a condition that obviously does not hold at the depth at which ore-forming processes operate.

The critical temperature of water is lowered considerably by the presence of CO_2, H_2S, and HCl. The presence of the alkali chlorides and the chlorides of the common metals tends to raise the critical temperature of the resulting mixture, but their amounts are hardly likely to be high in comparison to the former, hence their effect will not be great. Thus it is evident that there is a possibility that the critical temperature of the gaseous portion will be so low that its effect will be noticed in the mesothermal zone, since, according to Lindgren,[21] the temperature at which the mesothermal veins were formed is probably between 175° and 300° C.

If lead and zinc are transported from the magma as volatile chlorides, and are in contact with H_2S, it should be expected that

[19] Lindgren, W.: Mineral Deposits, p. 599, 1928.
[20] *Op. cit.*, p. 71.
[21] *Op. cit.*, p. 598.

the sulphides will be deposited, provided a calcareous environment is encountered whereby the HCl will be neutralized. Otherwise the mass-action effect of the HCl would prevent the sulphide from being deposited. The chlorides of lead and zinc below the temperature at which they are volatile would be taken into solution and transported as the soluble chloride.

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS, MINN.,
June 27, 1935.

A GOLD–BISMUTH OCCURRENCE IN BRITISH COLUMBIA.

HARRY V. WARREN.

ALTHOUGH in British Columbia gold is frequently associated with arsenic and antimony, it is seldom found with bismuth. Furthermore, gold bismuth occurrences in which the bismuth occurs as cosalite or galenobismutite, bismuth lead sulphides, are rare. Consequently a brief description of a deposit of this type, with particular reference to the mineralogy and its significance, is of interest.

The Cariboo Gold Quartz Mine shows widespread gold-cosalite mineralization, and samples generously supplied by the management have provided the material for this investigation. The mine is situated near Barkerville, in the Cariboo Mining Division of British Columbia.

PREVIOUS DESCRIPTIONS.

Descriptions of the mine have appeared from time to time,[1] and the general geology has been described also in reports of the Canadian Geological Survey, especially by Uglow,[2] who gives references to all previous workers, including Amos Bowman, Mackay, and others.

However, since Dr. Uglow's untimely death new facts have come to light, and it is particularly with this new mineralogical evidence and its bearing on the old ideas as to the age of the deposits in the area, and as to the origin of the related placer gold, that this paper is concerned.

The introductory general geology is culled from the above-mentioned reports and is intended to serve only as a background.

[1] Annual Reports, British Columbia Minister of Mines, 1922 *et seq.*

[2] Uglow, W. L.: Geological Survey of Canada, Mem. 149, 1926.

GENERAL GEOLOGY.

The ore in the Cariboo Gold Quartz Mine occurs in quartz-filled fissures that pinch and swell along the strike, and range in width from a few inches up to ten feet. These fissures occur in sheared pre-Cambrian (?) quartzites. The vein quartz is likewise much sheared. The veins cut the schistose formation on strike and dip, the latter generally being steep.

The quartz veins are mostly heavily mineralized with pyrite, which may be massive or well crystallized in large or small cubes. The pyrite content ranges from 10 to 25 per cent by weight. Cosalite and galenobismutite commonly accompany the pyrite, and the presence of these bismuth minerals is an excellent indication of high gold values. Other sulphides are rare.

MINERALOGY.

The following minerals have been identified in the samples submitted: gold, galena, sphalerite, pyrite, quartz, galenobismutite, cosalite, telluride (variety unidentified), ankerite.

Gold.—occurs in particles readily visible to the naked eye in many samples but is most prominent in the galenobismutite and cosalite. It also occurs in intimate physical relationship with the pyrite. Here, however, the gold particles are generally so small that they cannot be determined even under the microscope.

Galena.—is abundant in pockets in the upper level of the mine, and some gold and silver is associated with it.

An assay of some galena, which megascopically appeared to be uncontaminated, ran as follows: Pb 84.30 per cent.; Ag 1.05 per cent.; S 13.70 per cent.; Au 0.48 oz. per ton.

Polished sections indicate that some, if not all, of the precious-metal content of the galena is the result of included impurities.

Sphalerite.—occurs associated with the galena. It has not been possible to pick out a sufficient amount of the pure material to make an analysis.

Pyrite.—is the most prominent sulphide in the ore and occurs both in massive form and in well developed cubes. Samples of

both varieties were picked out and assayed with the following results:

(*a*) Small cubes	(1)	0.62 ounces of gold per ton.
Small cubes	(2)	0.56 ounces of gold per ton.
(*b*) Large cubes		0.16 ounces of gold per ton.
(*c*) Massive	(1)	0.75 ounces of gold per ton.
	(2)	0.20 ounces of gold per ton.
	(3)	1.53 ounces of gold per ton.

Preliminary polished sections failed to show any free gold in pyrite, but later in more highly polished sections gold in minute veinlets was seen cutting pyrite. Consequently, although it is true that the gold is associated with pyrite, it is probable that the association is mechanical or electro-chemical rather than chemical. Quite probably the gold was precipitated on the pyrite by some interaction between the gold-bearing solutions and the pyrite. This is suggested by the fact that the gold content of the small cubes is far higher than that of the large cubes.

Some of the pyrite was also analyzed for iron and sulphur with the following results:

	Iron.	Sulphur.	Total.
	%	%	%
(*a*) Small cubes	46.5	51.9	98.4
(*b*) Large cubes	46.6	51.9	98.5
(*c*) Light-colored massive	46.4	51.7	98.1

The light-colored massive variety has often been spoken of as arsenical pyrite. A small sample was tested for arsenic with negative results.

Galenobismutite ($Pb\ Bi_2S_4$).—This rare mineral, which is of considerable interest because of its association with gold in Idaho,[3] was determined by chemical analyses and by etching tests under the microscope. It is massive, and therefore differs from its usual form of occurrence. Some material was separated and assayed with the results shown below. These compare closely

[3] Shannon, E. V.: Jour. Wash. Acad. Sci., vol. 11, p. 298, 1921.

with Shannon's analysis of the Idaho material[4] and with two analyses by Dana.[5]

	S.	Bi.	Pb.	Fe.	Cu.	Sb.	Total.
Cariboo	16.40	51.00	30.50	1.50	—	—	99.40
Shannon	17.80	53.59	23.93	.39	1.73	2.56	100.00
Dana (*a*)	17.35	54.69	27.65	—	—	—	99.69
Dana (*b*)	16.78	54.13	27.18	—	—	—	98.09

It will be noticed that the Cariboo galenobismutite is somewhat high in lead and low in bismuth. Under the microscope some cosalite could generally be seen with the galenobismutite, and this appears readily to explain the above discrepancy.

Free gold is associated with the galenobismutite, occurring through the sample as fine stringers and occasional small "nuggets."

Sufficient material has not yet been separated to enable an assay to be obtained of the silver present.

Cosalite ($Pb_2\ Bi_2\ S_5$).—This mineral is also rare but its chief claim to interest is that, like the galenobismutite, it is intimately associated with the gold that occurs in the mine. The cosalite was determined by chemical analysis and by etching tests on polished surfaces. An analysis of as pure material as could be obtained, as compared with the material originally determined as cosalite,[6] is as follows:

	Lead.	Bismuth.	Sulphur.	Silver.	Copper.	Total.
Cariboo	41.20	39.35	16.40	—	3.60	100.55
Dana (*a*)	40.32	41.76	15.27	2.65	—	100.00
Dana (*b*)	38.79	42.77	15.23	3.21	—	100.00

It will be noticed that the bismuth is somewhat low for the theoretical composition of this mineral, but as copper and bismuth readily form an eutectic, it is probable that copper replaces bismuth in part. If this is assumed, the assay is theoretically all

[4] *Idem.*

[5] Dana, E. S.: System of Mineralogy, 6th Ed., 1914, p. 114.

[6] *Idem*, p. 121.

but perfect. Small amounts of copper have often been found in cosalite, so this assumption seems to be justified.

The cosalite occurs in fibers and acicular masses and is the mineral that has probably been mistaken for chiviatite and bismuthinite, both of which it superficially resembles. The mineral is usually veined by gold, which also occurs as scattered "nuggets." In places, the gold in the cosalite amounts to as much as ten per cent of that mineral by weight. Often the gold can be observed in the cosalite with the unaided eye, but sometimes it can be seen only under the microscope in polished sections or after dissolving the cosalite in acid. One sample of cosalite which showed not even a trace of gold under binoculars, when assayed was found to contain 44.5 ounces of gold to the ton. It is easy to realize the "sweetening" effect of material of this richness.

Telluride.—Tellurium was detected during an analysis of one of the galenobismutite samples. A mineral, present in specks too small to be determined, was seen in one section intimately associated with gold. This is believed to be the tellurium mineral, but nothing further can be said at the present time.

Quartz is by far the most important gangue mineral and occurs abundantly throughout the mine. Several samples free from visible gold were assayed, and none gave even a trace of the precious metal.

Ankerite, together with related carbonates, occurs sparingly as a gangue throughout the ore.

Paragenesis.—The paragenesis of the ore has not yet been fully worked out. It is probably as follows (the oldest mineral first): pyrite and quartz; pyrite; galena and sphalerite; ankerite (?); cosalite, galenobismutite, and gold.

THE MINERALOGICAL SIGNIFICANCE.

The mineralogical significance of the deposit is important. In the first place there is little doubt as to the hypogene origin of the gold. Formerly, the free gold of these veins was considered to

be supergene and the result of oxidization of auriferous pyrite and arsenopyrite.

Uglow [7] writes: "Free gold was found only in the upper, disintegrated, and decomposed parts of the veins, but not in quantities that seemed large enough, nor of the proper character, to be the source of supply of the gold for the rich placers."

Secondly, it seems clear that at least the bulk of the placer gold in the Barkerville area was derived from "nuggets" occurring in eroded portions of veins rich in cosalite and galenobismutite, these minerals apparently having the ability to precipitate coarse gold in a manner not rivalled by pyrite and arsenopyrite. Hanson has already drawn attention to this phase of the origin of gold in these placers.[8] Uglow did not have available the information possessed today, and it is not surprising under the circumstances that problems of the formation of the gold placers in the Barkerville area assumed a complexity entirely unnecessary in the light of present knowledge.

In the third place, although occurrences of galenobismuth and cosalite are rare, the meager evidence available suggests that they represent a relatively low-temperature type of mineralization and were formed at moderate to low depths.

The Barkerville area has been an area of erosion since Mississippian time, as far as the present evidence indicates, and yet the mineralization is attributed to the Palaeozoic or pre-Cambrian. Surely this amount of erosion is pitifully small for this length of geological time. However, admittedly good evidence has been collected in the field to substantiate this belief. Nevertheless, on mineralogical grounds, I believe that it would be wise to consider that possibly this mineralization may be related to the later Mesozoic intrusives found in the Quesnel Forks area by Cockfield.[9] By attributing a younger age to the Barkerville mineralization, it could then be related readily to other gold occurrences in British Columbia and the Western United States.

[7] *Op. cit.*, pp. 214–219.

[8] Hanson, George: Canada Geol. Surv., Summ. Rept. 1933, Pt. A, p. 48.

[9] Cockfield, W. E.: Canada Geol. Surv., Summ. Rept. 1932, Pt. A, pp. 81, 82.

SUMMARY AND CONCLUSIONS.

The two hitherto undetermined minerals at the Cariboo Gold Quartz Mine are two simple lead-bismuth sulphides, cosalite and galenobismutite. Free gold shows a strong affinity for these two minerals. The intimate relationship of gold with these fresh and unaltered lead-bismuth minerals explains readily the origin of much of the placer gold in the Barkerville area, and furthermore proves beyond doubt the hypogene nature of the ore bodies.

On solely mineralogical grounds it seems advisable to investigate more fully the possibility that these ore bodies are Mesozoic in age and may therefore be related to the majority of gold deposits found elsewhere in British Columbia.

ACKNOWLEDGMENTS.

The majority of the specimens which were studied were supplied by the courtesy of Dr. W. B. Burnett, Mr. Solibakke and Mr. Rose.

All this work was done in the laboratories of the University of British Columbia; the assays were made by Mr. Johnson, and the polished section and other laboratory work was largely done by Mr. Johnson and Mr. Maconachie. The writer is also indebted to Mr. Eldridge, of G. S. Eldridge and Company, for running the check assays which were considered necessary in determining such unusual minerals as cosalite and galenobismutite.

The late Dean Brock and Dr. Schofield, of the Department of Geology, and Drs. Cockfield and Walker, of the Geological Survey of Canada, should also be mentioned for their kindness in discussing this paper and their advice throughout its preparation.

UNIVERSITY OF BRITISH COLUMBIA,
VANCOUVER, B. C.,
May 15, 1935.

A SIMPLE METHOD OF MAKING, MOUNTING, AND FILING POLISHED SECTIONS.

B. M. SHAUB.

MANY methods of making polished sections of opaque minerals have been described.[1] Most of these involve the grinding of a flat smooth surface on a chip by means of a rotating power lap of either metal or glass, and subsequent grinding by hand with finer powders on metal or glass plates. The polishing is done on rotating fabric-covered laps with different kinds and grades of polishing powders to suit the nature of the ore specimens. The Vanderwilt method of polishing involves the use of power-driven mechanically operated lead laps carrying embedded in the metal a fine, carefully sized polishing powder. The results are of the highest order obtainable. However, the cost of the apparatus prohibits its adoption by most workers in mineragraphy. All these methods use a more or less cumbersome mount which does not readily lend itself to labeling and filing without special accessories.

The method devised by the writer for preparing polished sections is believed to be somewhat simpler in its procedure, to produce a section having a polish somewhat better than the average section polished on a fabric lap, and it provides a mount equally or more convenient for microscopic use and superior for labeling and filing.

[1] Campbell, William: The Microscopic Examination of Opaque Minerals. ECON. GEOL., vol. 1, pp. 751–766, 1905–06. Whitehead, W. L.: Notes on the Technique of Mineragraphy. ECON. GEOL., vol. 12, pp. 697–716, 1917. Schwartz, G. M.: Preparation of Polished Sections of Ores. ECON. GEOL., vol. 22, pp. 193–195, 1927. Short, M. N.: The Preparation of Polished Sections of Ores. ECON. GEOL., vol. 21, pp. 648–664, 1926; Microscopic Determination of the Ore Minerals. U. S. Geol. Surv. Bull. 825, pp. 10–17, 1931. Van der Veen, R. W.: Mineragraphy and Ore-Deposition, vol. 1, pp. 6–13. G. Naeff, The Hague, 1925. Vanderwilt, J. W.: Improvements in the Polishing of Ores. ECON. GEOL., vol. 23, pp. 292–316, 1928.

PREPARATION OF THE SECTION FOR POLISHING.

The section is obtained by cutting one of the desired size from a selected chip or hand specimen (Fig. 1-*a*) by means of a dia-

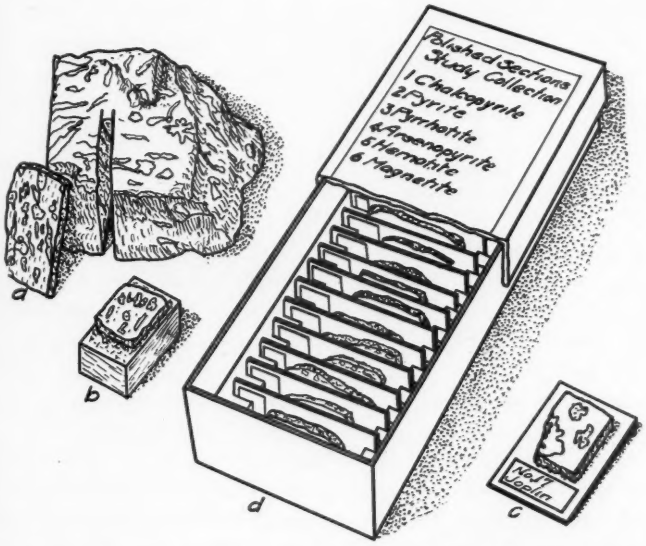

FIG. 1. Section (*a*) sawed from a hand specimen; (*b*), mounted on a wooden block for polishing; (*c*), mounted on bakelite for examination; (*d*) manner of filing in thin-section boxes.

mond saw constructed with a mechanical feeding device [2] which enables the technician to cut a chip with parallel sides and of any desired thickness. The thickness of the chip will depend upon the nature of the specimen and may be about 0.1 to 0.2 inch. Friable ones must be thicker, or a special treatment with bakelite or other cements or resins [3] may be necessary. The saw used for

[2] Shaub, B. M.: An Inexpensive Rock Slicing Machine. ECON. GEOL., vol. 30, pp. 916–922, 1935.

[3] Ross, C. S.: A Method of Preparing Thin Sections of Friable Rocks. Amer. Jour. Sci. (5), vol. 7, p. 483, 1924. Method of Preparation of Sedimentary Materials for Study. ECON. GEOL., vol. 21, pp. 454–468, 1926.

cutting the section should have parallel sides at the periphery and not flare out in a bead which will cut deep circular grooves in the section. Considerable grinding is necessary to remove such grooves unless coarse powder is used, and this rough procedure should be avoided because with friable or cleavable minerals it develops deep pits. The diamond dust used for charging the saw should be fine and uniform. The saw should run true, and one gains in the end by using a slower feed. These precautions will prove helpful regardless of the system used in polishing.

The grinding operation on the chip may be done either on plate glass, or on glass or copper laps using successively finer fractions of 600 Alundum or Carborundum powders. The metal laps should be free from coarse embedded grains of abrasive. The finer the matte or the sub-polished surface one can produce by grinding on a copper lap with the finer floated powders, the easier the polishing operation becomes and the less relief is developed. The final grinding is done with levigated alumina from which coarse material has settled, after shaking with water in a large bottle and allowing it to stand for ten to fifteen minutes.

The Polishing Lap.—In the polishing operation a sole-leather lap is used instead of fabrics; its use is believed to be new in the polishing of opaque minerals and was selected because its surface is firm and will hold in place, to a surprising degree, the very fine polishing powder. These are important features in polishing in order to avoid excessive relief. However, the time required to obtain a polish is increased with the fineness of the powder, especially with the harder minerals.

The support for the sole leather, which should be of uniform thickness to avoid excessive vibration, is a 9 inch aluminum disk whose surface is thoroughly cleansed. The leather may be attached, flesh side against the metal, by the use of Duco Household cement. Considerable pressure should be applied to the leather after adjusting it to the disk by clamping a similar disk to the face of the leather. Several days are required for the cement to dry. After the clamps are removed the leather can be neatly trimmed at the periphery of the disk by means of a sharp

pocket knife. The lap is then mounted on an armature of a quarter-horsepower motor (Fig. 2), and operated at 1725 R.P.M. If for any reason more than one lap is desired, the interchange

FIG. 2. Sole-leather lap attached to an aluminum disk and mounted on the armature of a quarter-horsepower motor.

can be made quickly. The life of the sole leather is unknown; for ordinary use during two years the leather surface has not been materially affected, instead it has improved after first being put into service.

Preparation of the Polishing Powder.—The powder used for polishing, which may be done in one stage for all specimens, consists of levigated alumina which has remained in suspension at the end of two hours. Approximately one-half pound of the commercial powder is shaken up in a one-gallon bottle; after two hours, three-fourths of the solution is siphoned off and allowed to settle in a shallow flat-bottomed pan from which the remaining water can be removed by decanting, siphoning or using an aspirator. The floated powder should be stored in small screw-capped jars until required.

The Polishing Technique.—At first the surface of the lap is moistened with kerosene or a light lubricating oil by holding a

cloth, well wetted with the liquid, against the lap while it is rotating. After the leather has taken up sufficient oil to repel water, the wetness of the oil or kerosene cloth should be reduced when used for removing expended powder. The dry powder is moistened with water in a small glass dish and applied uniformly in a thin coating to the leather while at rest by means of the finger tips, which should be free from grit. If the leather contains too much oil a gum will be likely to form on the face of the specimen. This not only prevents polishing but disturbs the distribution of the powder. If the leather is kept wet with water it may bulge and form blisters at places; in addition, the specimen has a tendency to seize. A bumpy and uneven distribution of the powder is obtained if one applies it with a brush or cloth, and besides, more than 50 per cent. of the polishing material is lost. There seems to be very little shifting of the powder over the lap during polishing, and the fine material removed from the specimen adheres to the powder on the leather. At intervals the old powder and material removed from the specimen should be cleaned from the lap with a cloth slightly wetted with kerosene. The last of the old powder remaining on the lap is removed with a cloth, moistened with water, before it is given another application of fresh powder. The progress of the polishing should be checked with a hand lens or reflecting microscope. When the desired polish is obtained, most of the fine scratches may be removed by holding the specimen very lightly against the central part of the lap after it is freshly charged. Specimens which are brittle and friable and continually " shedding " small particles are almost impossible to polish without retaining small scratches in the softer minerals. This also applies, and I believe to a somewhat greater degree, with the ordinary fabric-covered laps. The writer has used the preceding technique with good results for both hard and soft minerals. Other operators may, by varying the procedure, obtain equal or better results from the many possible combinations that may be adopted.

Mounting the Chip for Polishing.—A chip of only 0.1 to 0.2 inch thick cannot be readily held in the fingers during the polish-

ing operation. A convenient and satisfactory procedure is to cement the chip to a small rectangular block of hardwood (Fig. 1-*b*) by using a *thin* layer of cement of equal parts of sealing wax and stick shellac. Both the chip and the block should be heated before mounting and allowed to cool in the air. This cement softens slowly, so that the sliding of the chip on the block can be noticed in ample time to prevent it from getting away. If the layer of cement is very thick, brittle chips are quite likely to break if the cement softens and flows from under the hotter part. One should work with several specimens at a time, and when one warms up it can be placed face down on a clean, smooth, metal plate which readily removes the heat. Minerals that are likely to revert to other forms when too hot, may be polished and mounted at a comparatively low temperature. Upon completing the polish, the section can be removed from the block by placing it face down on an object glass on a hot plate until the cement has softened. The cement adhering to the chip can be removed with a knife.

Mounting the Section for Examination, Labeling and Filing.—After the section is removed from the holding block, it is mounted on a rectangular piece of bakelite (Fig. 1-*c*) the size of a standard petrographic object glass and 1/16 inch thick.[4] It can easily be cut to the required size on a small wood-working table saw. The polished section is attached to the bakelite by means of bakelite cement, BC–6052,[5] which makes a firm bond.

A brief description of the specimen can be attached to the upper surface of the bakelite by means of a gummed label. The section can be used on the microscope stage in the same manner as a thin section, and if it is not more than about 1/5 inch thick it can be filed in an ordinary thin-section box unless the slots are too narrow and close together. Both thin and polished sections from

[4] This material, in sheets of 21 square feet, can be obtained from the Formica Insulation Co., 145 Hudson Street, New York, for $7.56 per sheet. A Delta abrasive saw No. 227 cuts it satisfactorily.

[5] This may be purchased from the Bakelite Corporation, New York, at one dollar per can. The total cost of a mount is about 2½ cents.

the same locality or from the same specimen may be filed together.

Larger sections may be easily prepared and mounted on pieces of bakelite corresponding in size to the large thin-section object glass, 52 × 75 mm., and filed in the boxes used for the larger slides.

A distinct advantage in using these low mounts is the possibility of examining the section on most of the lower priced Leitz microscopes in conjunction with their vertical illuminator.

Repolishing Tarnished Sections.—When a section is mounted, it may be repolished by holding it in the fingers and pressing it lightly against the lap.

Department of Geology, Smith College,
Northampton, Mass.,
Sept. 26, 1935.

DISCUSSION AND COMMUNICATIONS

THE TIN DEPOSITS OF LLALLAGUA, BOLIVIA.

Sir:—Dr. Turneaure's paper [1] on the tin deposits of Llallagua is a valuable contribution to the genesis of these unique deposits. I take the liberty of presenting my opinion, based upon my large experience with Bolivian tin deposits, regarding some points in his paper.

I agree with the author in the essential points, but my microscopic examinations of ores revealed some different results respecting the paragenesis of minerals. (See Turneaure's Fig. 10, graphical representation of mineral sequence.) The formation of tourmaline and cassiterite overlaps slightly, as is shown by the occurrence of tourmaline needles on cassiterite crystals. Cassiterite and wolframite similarly overlap. The early formation of bismuthinite, before wolframite and cassiterite, mentioned by the author, is unusual; however, I observed similar cases in other Bolivian deposits, *e.g.* Cerro de Potosi and Chorolque. At Llallagua there also is later bismuthinite replacing stannite.[2] Arsenopyrite occurs always with early sulphides as veinlets or crystals in pyrrhotite or as massive vein fillings. Replacement of the pyrrhotite by marcasite-pyrite has left residuals of arsenopyrite in marcasite-pyrite.

I agree with the author regarding the replacement of pyrrhotite by marcasite-pyrite during the last stage of hypogene mineralization, and also as to the fact that this process extends to all zones. It was produced through a kind of "autohydration" of the intrusive by residual aqueous solutions, probably alkalic, containing

[1] Turneaure, F, S.: The Tin Deposits of Llallagua, Bolivia. ECON. GEOL., vol. 30, pp. 14–60, 170–190, 1935.

[2] Ahlfeld, F.: Ueber Zinnkies. Neues Jahrb. Min. B.B. 68, Abt. A, 1934, pl. 8, Fig. 7.

much H_2S. These affected principally the pyrrhotite, whose cleavage (along 0001), invisible in fresh pyrrhotite, appeared by partial solution. The spaces between the pyrrhotite plates were filled by franckeite, which to a great extent has been replaced by later pyrite. According to my observations, the franckeite of Llallagua belongs to the late phase of "replacement of pyrrhotite." Turneaure's Fig. 21 does not prove that franckeite is older than pyrrhotite and replaced by it. I have never seen fresh pyrrhotite with franckeite. Siderite likewise was formed by replacement of pyrrhotite, and many samples contain inclusions of franckeite in siderite of the same generation. The age of the franckeite at Llallagua corresponds, therefore, with that of franckeite in other Bolivian deposits.[3]

The latest hypogene minerals were rhodochrosite, sphalerite with colloform texture, chalcopyrite, crystallized marcasite and wavellite, all in small amounts.

As to the zonal distribution of minerals, the author speaks of "a high-grade cassiterite core and a low-grade sulphide shell." Based upon physico-chemical conditions, which below the rich cassiterite zone must have been other than above it, a mineralization in the vicinity of the magma different from that near the surface must be expected. This proved to be true.[4] At the outcrops of many of the veins, minerals of a mesothermal and epithermal type were found. I had at my disposal a number of specimens, collected by Mr. H. Block, manager of the Uncia mine in 1908, from the upper 200 meters of the deposit. Among these there are many samples of pure stannite, of tetrahedrite, franckeite in compact vein fillings, wurtzite, also manganese-rich wolframite (hübnerite), which is so characteristic for the epithermal stibnite veins in Bolivia.[5] Gmehling [6] gives the following description of

[3] Moritz, H.: Beitrag zur Kenntnis der Sulfostannate Boliviens, Teil II. Neues Jahrb. Min. B.B. 66, Abt. A, pp. 191–212, 1933.

[4] Ahlfeld, F.: The Tin Ores of Uncia-Llallagua, Bolivia. ECON. GEOL., vol. 26, pp. 241–257, 1931.

[5] Ahlfeld, F.: Ueber die Verteilung des Wolframs in der bolivianischen Zinnprovinz. Chemie der Erde, vol. 7, pp. 121–129, 1932.

[6] Stelzner, A.: Die Silber-Zinnerzlagerstätten Boliviens. Zeit. deutsch. geol. Ges., vol. 49, p. 129, 1897.

the outcrops of the Uncia-Llallagua deposit: "In tieferen Regionen nimmt der Gehalt an Zinnerzen (mit wenigen Ausnahmen) mehr und mehr ab, der an Silbererzen zu; in der Regel sind letztere Antimonverbindungen."

Certainly in other veins much cassiterite and marcasite-pyrite, formed by the oxidation of pyrrhotite, were already to be found near the surface.

As to the deepest zone, the epi- and mesothermal minerals mentioned above are missing, also the bismuth minerals. Apart from scanty cassiterite, much marcasite-pyrite, and small quantities of franckeite, formed in the way described above, arsenopyrite, pyrite and black sphalerite occur, all formed at high temperatures. The change of veins rich in cassiterite above, into sulphidic veins with sphalerite and pyrrhotite in depth, is well known in Bolivia. The occurrence of marcasite-pyrite and franckeite in the deeper levels is to be explained by the fact that the last phase of mineralization has equally affected all zones. As to the formation of tourmaline, the author is right when he says that the tourmalinization has affected the whole intrusive rock, but in the near-surface zone there is no tourmaline, or scarcely any, in the veins, and in the deepest levels many of the veins are strongly tourmalinized.

I believe that, according to the evidence given above, the three vertical zones described by myself from Llallagua are well established. I also found the same zonal distribution of minerals at Avicaya and at Chorolque, in deposits which have a certain similarity with those of Llallagua.

The lateral zoning at Llallagua can be studied very well in the peripheral zones of the Salvadora neck. Many veins in the sediments are partly associated with pyrite, black sphalerite and small quantities of cassiterite in the form of needle tin, as is characteristic in mesothermal and epithermal Bolivian deposits. Thus, in the southeast part of the Uncia mine and nearly one kilometer distant from the contact, Mr. Oropeza works two veins, one with pyrite, sphalerite and needle tin, the other with tetrahedrite.

FRIEDRICH AHLFELD.

LA PAZ, BOLIVIA,
Dec. 6, 1935.

REVIEWS

Ore Deposits of the Western States (Lindgren Volume). A collaboration by forty-four American geologists; JOHN WELLINGTON FINCH, Chairman of Editorial Committee. Pp. xxxiv + 797, figures 63. American Institute of Mining and Metallurgical Engineers, New York, 1933.

Reviews that have already appeared since the publication of this unique work have amply disclosed its general scope and character and have warmly praised both the purpose and the result. One who would now discharge the assignment of reviewing this volume need therefore not essay the usual comprehensive and balanced commentary on the contents as a whole, but instead may direct attention chiefly to certain topics and treatments in the book that seem to court special consideration.

The decision to publish a volume dealing with ore deposits and dedicated to Professor Lindgren has proved wise beyond all forecast. The highly successful and valuable Posepny Volume and Emmons Volume, previously published by the Institute, had, in large measure, been accumulated from quite spontaneous writings already extant, with the addition of certain made-to-order chapters by a few well-qualified investigators upon such chance subjects as these individuals felt inclined or inspired to contribute. The preparation of a brand-new work that would constitute a comprehensive yet unified and consistent treatise on the varied ore deposits of the Western States was obviously a far more pretentious and difficult undertaking, the feasibility and success of which were viewed with no little uncertainty by several of those who gave counsel. For experience has so often shown that plans for elaborate symposia involving many contributors of diverse views, experience and temperament result in poor cohesion and balance, as well as in complete lack of sparkle and inspiration.

The surprising degree to which the present volume has attained coordination and consistency without becoming forced or heavy, and has blended synopsis of a vast literature with useful generalization and even with new conceptions of first importance, stands as a fine tribute to those of the Institute Committee who, led by the enthusiasm, tact and unremitting zeal of Doctor Finch, were chiefly responsible for the plan of the book, for the allocation of topics, and for the really stupendous job of censorship and editing. Yet these and many others who contributed

realize fully that the task was immeasurably simplified by the very circumstances that brought the project into being. For the finished volume gives immediate evidence of its profound dependence in scope and arrangement on Lindgren's own "Mineral Deposits"; the method of approach to the problems attacked and the soundness of conclusion reached by the authors are direct fruits of their tutelage—much of it at first hand—under this Master; while the remarkable zest and flavor of the whole but measure the inspiration exerted upon all by Lindgren's genius and character. It is indeed to be doubted if any other *Festschrift* in the field of science has exemplified a more spontaneous tribute to a leader or has afforded a more readable and valuable record.

This is not to ignore some obvious limitations and shortcomings. The natural tendency and the deliberate desire to select authors largely from among associates and disciples of Lindgren undoubtedly gives to the result a slant which is not entirely representative of present-day American thought on ore deposition; it is rather the measure of Lindgren's influence on that thought. There is, of course, nothing insidious in this—no covert plot by a group of zealots to warp the record. Those few manuscripts sought or proffered which were at last rejected or declined were assuredly not judged by the test of "conformism." And of all those comments seen by the present reviewer, the only one[1] which intimates the use of heavy-handed methods in the preparation of the volume wastes its humor by confounding ores of magmatic derivation with "ore magmas." Moreover, it is not to be overlooked that various contributors who may agree in subscribing to a general consanguinity of ores and magmas nevertheless are here found expressing views almost diametrically opposite on specific matters vitally affecting that more general thesis.

In short, what we see is a snapshot of contemporary opinion on a broad and diversified subject. Some confusion, some contradiction, and indeed probably some unconscious bias are inevitable. The degree of agreement may be taken as a suggestive but not as yet entirely reliable index of the advance in understanding of the complex and still speculative subject of ore deposition; the extent of disagreement intimates something of the long path that must still be travelled before it can fairly be concluded that the subject has been substantially mastered.

It is hardly to be doubted that, at least from some points of view, too many cooks have had a hand at the broth. It was evident that if topics of such wide range were to be handled in each case by a specialist, a considerable list of authors would result in any case. But the exigencies of completion within a reasonable time and the invariable burden of

[1] Ore Magmas and the Lindgren Volume. Mining and Metallurgy, vol. 15, Oct. 1934, pp. 420–421.

competing obligations on those most naturally to be selected for authorship led in several instances to subdivision of topics and the farming out of "sub-leases," which, together with the ever-present evidences of condensation, are not conducive to easy reading. Nevertheless, the conscientious student finds relatively little that is obscure or ambiguous.

The book could unquestionably have been more unified and consistent had there been greater interchange of views among the several authors; for there are now recorded in it numerous differences of view or of emphasis that probably need not persist. Only a few of the contributors had opportunity to examine the entire manuscript and to modify their own respective sections harmoniously therewith. But here again the practicality of prompt completion had to govern. Mere multiplication of authors is doubtless partly responsible also for the high degree of descriptive detail embraced in some of the longer chapters, where in some instances merest reference to the original sources might perhaps have sufficed.

This leads to the question of the ultimate usefulness of the book. It will, of course, be eagerly and conscientiously read from cover to cover by specialists in the study of ore deposition. But will time prove that they come back to it again and again for re-inspiration by such of it as is new and constructive, and for time-saving use of its assembled references to a wide literature? The present reviewer is inclined to question whether frequent and sustained recourse to this as a reference volume will not be materially lessened by its close patterning in so many respects upon Lindgren's "Mineral Deposits," on which we have all learned to depend and which the fourth edition, published since the Lindgren Volume, carries to even greater usefulness.

Will the "general" geologist recognize that in this "practical" volume there is a wealth of "pure" science? Will the mining engineer and mine manager investigate with open-minded and receptive attitude this record of the advances in the study of ore deposition beyond their own more meager and empirical impressions, on which all too many of them feel content to base important judgments; or will they look with thinly-veiled condescension on this as merely a more pretentious addition to the "high-brow" and "theoretical" deluge with which they feel they are being swamped? Even the excellent chapter on "Utilization of Geology by Mining Companies," written by men who have made most creditable records in this special field of practice, may well fail to exert its full illuminating effect either on mine operators or on those who approach the study of ores and ore deposition with less regard to its direct and exacting applications.

To raise these queries is by no means to imply that they are all to be answered adversely, but rather to emphasize the variety and complexity

of factors that determine the reception accorded to a large and diverse volume such as this. In view of these imponderables, forecast is difficult as to the exact place the book will hold ten or twenty years hence. But no one who reads the volume with care can fail to feel thankful that it has been brought out.

Comment may now be centered on those two portions of the book which appeal to the present reviewer as of outstanding interest.

While the emphasis placed by some practicing mining geologists on the great importance of structural controls has in too many instances crowded out adequate consideration of those more subtle and less-understood but no less fundamental physico-chemical influences on ore localization, it can hardly be doubted that, on the other hand, vitally important features of structural detail have too frequently been missed or slighted by those particularly interested in the broader and necessarily more speculative questions of ore deposition in general. In considerable measure the present volume reflects the second of these habits. It would seem that in this volume there was room, and indeed need, for a consideration of structure—in the specific sense ordinarily understood in mining geology—on a basis correlative in rank with that accorded in Chapter III to physico-chemical considerations. This gap has been only partly filled and at the same time has been emphasized by the interesting and highly suggestive summarized treatment of structural features for a few typical districts in Chapter XII devoted to application.

Diagnostic ear-marks of a given chemico-mineralogical type of ore, and hence some plausible ideas as to the physico-chemical conditions of its formation, may often be grasped by relatively brief inspection of the occurrence in question. The structural truth, on the other hand, is often to be had only through day-by-day and year-by-year contact with the given ore body or mine or district. Such intimate and maintained contact is almost never possible for the government geologist and still less for the itinerant college professor. Since these are the principle makers of the literature, it follows that the fundamentally important matter of structural control is, on the whole, inadequately dealt with in present-day writings.

It is therefore particularly to be regretted that a volume which owes so much, both in financial support and in scientific opportunity, to the practical mine operations of the West should not in a more deliberate and organized way have discussed the bearing of the immediately surrounding structures on ore deposition. It seems reasonable to suppose that, if the desirability of such a chapter had been adequately recognized and a more searching canvass made for contributions from among the practicing mining geologists, a creditable and valuable "progress report" on this

subject could have been prepared that would fully measure up to the quality of other major subdivisions of the volume.

Structure on quite a different scale, however, is beginning to interest the student of ore deposition, and in the present volume finds expression, even if it be somewhat tentative and speculative. The scope of inquiry changes from the structural controls that localize individual ore bodies to those that determine the sites of mining districts and even of great metallogenetic provinces. The excellent section of Chapter VI by Butler and the still broader stimulating treatment by Lindgren in Chapter IV are indicative of a trend likely to command increasing attention from all, and worthy of further extension by the best brains in the profession.

Many will doubtless agree that the most valuable section of the entire work is Chapter III, which deals with physico-chemical factors of hypogene ore deposition. No subject is of more pressing interest at this time, none more needful of treatment by experts. To realize that this portion of the work is handled by men primarily of geological training who have acquired such contact with physico-chemical and thermodynamic principles as to enable them to speak authoritatively thereon is at once reassuring. But if those far more numerous geologists whose background is not thus satisfactorily rounded out hoped to find here a clear, connected, self-consistent and fact-fitting explanation of the physico-chemical processes by which the magma yields ore deposits, they were doomed to a considerable measure of disappointment. For, highly stimulating and valuable though the several contributions are, the person who reads them with critical care must wince at finding still such evidences of disagreement among the investigators in these supposedly more "exact" branches of science as applied to the problem of ore deposition.

Just as a mathematical derivation is no more valid than its premises, so the application of physical chemistry to ore genesis will inevitably lead to conflicting conclusions so long as the initial assumptions are widely at variance. It is just here that the difficulty lies in Chapter III. The attempt is stimulating; but the chief lesson to be drawn appears to be that we must gain better and more consistent conceptions as to the nature of confined magmas and as to what happens *at depth* (in contrast to near-surface phenomena) before real progress is assured. The content of this chapter cannot fail, however, to hasten efforts toward improved understanding of these fundamental matters that are still in a state speculative and obscure.

L. C. GRATON.

HARVARD UNIVERSITY,
CAMBRIDGE, MASS.

Tertiary Faunas: A Text-book for Oilfield Paleontologists and Students of Geology. Vol. I. The Composition of Tertiary Faunas. By A. M. DAVIES. Pp. x + 406, figs. 565. Thomas Murby and Company, London, 1935. Price, 22 s. 6 d.

The first volume of Tertiary Faunas, of which the second volume was noted in this journal some time ago (Vol. 29, 1934, p. 608) has at last appeared. It deals with the character of the fossils, the distribution and significance of which were discussed in Volume II. In the present volume the author has not attempted a new classification nor has he introduced new names. "I have tried," he says, "to place before my readers the alternative generic names they will find both in past literature and, so far as can be foreseen, in that of the immediate future; and I have had in each case to choose one name as the most correct and enclose the rest within square brackets. Where recent rectifications in nomenclature seem likely to be generally adopted, I have accepted them, but where there is a conflict of opinion as to which of several forgotten names should replace a familiar one, I have retained the latter."

The book is divided into six chapters, on foraminifera, echinoidea, lamellibranchia, gastropoda, other Tertiary invertebrata, and Tertiary vertebrata, and in addition it contains a postscript correcting misprints in Volume II, a very full index of the forms described, and a satisfactory general index.

Each chapter opens with a general discussion of the group to which it refers, and follows with a description of its orders, families and genera. The descriptions are very concise, but, since they are illustrated by outline schematic drawings, they serve their purpose admirably. Each chapter closes with a glossary of technical terms that apply to the group, and a selected bibliography. The illustrations are not intended to show the appearances of the forms illustrated, but to emphasize their specific and diagnostic characteristics.

In the chapter on Tertiary vertebrates, these forms, because of the complexity of their skeletons, are dealt with in outline only, "though it is hoped that it [their treatment] may be sufficient to start the finder of any vertebrate fossil on the right track towards its identification." The descriptions are confined mainly to teeth.

The book should be of value to the worker in Tertiary stratigraphy as a convenient condensed summary of Tertiary paleontology, though the classification employed may not be satisfactory to some students.

It is unfortunate that the book is printed on such heavy paper, since it is uncomfortable to handle and is not likely to withstand hard usage.

W. S. BAYLEY.

Geology and Ore Deposits of the Cripple Creek District, Colorado. By G. F. LOUGHLIN AND A. H. KOSCHMANN. Pp. 217–435, figs. 48. Colo. Sci. Soc., Proc., vol. 13, no. 6. Denver, Colo., 1935.

This excellent account of the geology of Cripple Creek will be welcomed by practising mining geologists and theoreticians alike. After the publication of Lindgren and Ransome's careful work of 1906 (U. S. Geol. Survey Professional Paper 54), a period of eighteen years elapsed without the presentation of any further comprehensive studies of this interesting and important district. In 1924 a restudy was begun by Loughlin and intensified in 1933 and 1934, when both authors gathered data for a report on a P.W.A. project for a drainage tunnel to serve much of the district and to drain even the lower levels. This publication assembles all earlier data. It is another of the very well presented recent publications of the Colorado Scientific Society, summarizing work financed in cooperation between the Colorado Metal Mining Fund, the Colorado Geological Survey Board, and the United States Geological Survey. This method of publication insures a more prompt release than is given the usual final report with its necessarily more elaborate illustrations and more complex format. It is only to be regretted that mapping the mines in the district could not be continued steadily and hence that considerable data were lost—another illustration of one of the most difficult problems facing State and Federal surveys alike.

It would be hopeless here to thoroughly review the geologic findings announced by the authors. In tracing the history of the region they begin virtually with the Laramide Revolution; to the reviewer the emphasis upon the westward direction of the thrusting in this region was a point of interest as bearing upon the nature of the faults that border the Front Range to the east. Following Laramide orogeny, three erosion cycles may be recognized, after which came vulcanism, one episode of which was the formation of the Cripple Creek crater. This vulcanism and the faulting and fissuring that preceded and followed it furnish the kernel of the geologic history.

Of special significance is the thorough and very largely successful attempt to analyze the fissuring that caused the ore channels. In this report, as in so many other recent works on ore districts, the emphasis on structural control of ore deposition is very heavy. The authors appeal to a well-defined series of fractures, the acute angle of whose intersections is in the southern quadrant, suggesting northward compression; along the intersections of these fractures, they believe, the upward rise of magma and gases was readiest. After the main crater was formed, any further compression resulted in still more shattering along the same zone, this conclusion being an application of Nadai's principle. While the argument

for this view is not quite as clearly and tersely developed as might be desired, and the evidence cited (*e.g.*, the fissure directions mentioned in paragraph 2, page 270, which literally "box the compass" and seem to the reviewer to be unconvincing) is not wholly satisfactory, there can be little doubt that the facts and the general trend of reasoning alike point in the right direction, and that an excellent piece of work has here been done in organizing what might otherwise have been numerous hopelessly confusing facts. The emphasis on the controlling importance of pre-volcanic deformation, as opposed to the upward thrust of the magma or its gases, is in contrast to the suggestions recently made by Dr. W. H. Emmons, who tends to minimize pre-intrusive deformation.

Thanks to this three-dimensional study, the detailed structure of the compound Cripple Creek crater, as well as of the smaller Cresson "blow-out," is now so well understood that it should furnish material of very great interest to vulcanologists, who seldom have accessible a picture of the changes at depth in the shape of a given vent. In the Cripple Creek volcano two main crater "roots" are distinguishable, and the south-easterly of these, in turn, separates into seven smaller "rootlets" with "islands" or ridges of pre-Cambrian country rock between.

Among the ore bodies, "collapse breccias" are recognized,—masses of volcanic fragments corroded to roundness. Three stages of mineralization are distinguished. The first might be regarded as quasi-pneumatolytic (purple fluorite, adularia, dense quartz, and coarse pyrite); the second yields essentially the same minerals, with carbonates; the third bears quartz and chalcedony, scalenohedral calcite, and fine-grained pyrite, some of which suggests marcasite. To the reviewer, the presence of the forms of calcite and pyrite described by the authors in the third group reminds strongly of the Mississippi Valley lead-zinc ores, in which scalenohedra of calcite and radiating "needles" of pyrite are again typical, at least locally. The tellurides are of importance in the second stage.

There are numerous black and white sketches of workings and diagrams showing the geology of the crater and adjacent rock, ore occurrence, and vein pattern. A special section deals with geologic aspects of the proposed new tunnel. All in all, the report is an excellent tribute to the painstaking and intelligent work of the authors.

CHAS. H. BEHRE, JR.

NORTHWESTERN UNIVERSITY,
EVANSTON, ILL.

Geography of North America. By G. J. MILLER AND A. E. PARKINS. 2d ed. Pp. 632, figs. 288. John Wiley & Sons, New York, 1935. Price, $4.50.

This comprehensive text has been largely rewritten. Part I deals with climate and with North America as a home for man. In Part II the physiographic regions are considered, and the major sections of the country with the land features, soils, industries, and commerce pertaining to each. Similarly, in Parts III and IV, Canada and Newfoundland, and Mexico and Middle America, are considered. The main scheme of treatment is by industries of the different sections, the consideration of which brings in discussions of the other geographic features. "Agriculture in the South," for example, treats of agricultural areas, population, farming methods, soils, climate, physical features, crops and marketing.

The book is authoritative, comprehensive, and should serve as a satisfactory reference and text.

An Outline of Geography. By P. E. JAMES. Pp. 475, pls. 24, figs. 182. Ginn & Co., New York, 1935. Price, $3.00.

In this interesting introductory text the author has rather successfully interwoven a discussion of land forms, plants, animals, and human communities. There are eight chapters, arranged according to land forms—The Dry Lands, Tropical Forest Lands, Grass Lands, Polar Lands, Mountain Lands, etc. Each is well illustrated by maps, charts, drawings, and photographs. A valuable appendix contains chapters on the Atmosphere, Lithosphere, and Hydrosphere. The chapter on the atmosphere elucidates modern meteorology. The appendix contains some really excellent block diagrams. A fine set of colored charts is included. The book is well balanced, interesting, and instructive.

BOOKS RECEIVED.

L. B. RILEY.

Historical Geology of the Antillean-Caribbean Region. CHARLES SCHUCHERT. Pp. 811, figs. 123. John Wiley & Sons, New York, 1935. $10.00. A monumental work summarizing the stratigraphy and historical geology, with correlations; a compendium invaluable to the stratigrapher and petroleum geologist. (To be reviewed later.)

Geology and Ore Deposits of the Casto Quadrangle, Idaho. C. P. Ross. Pp. 132, pls. 8, incl. colored map. U. S. Geol. Surv. Bull. 854, Washington, 1934. 60 cts. One of series of projects in south-central Idaho. Idaho batholith and Tertiary granitic rocks and dikes intrude sedimentaries. Some contact and other forms of lode deposits associated with both Tertiary and Idaho intrusives. Total production from

gold and copper lodes about a million dollars; an equal amount from placers; but little production since 1916.

The Southern Alaska Range. S. R. CAPPS. Pp. 101, pls. 8, incl. 2 colored maps. U. S. Geol. Surv., Bull. 862. Washington, 1935. 70 cts. Area of 27,000 sq. mi. west of Anchorage and Seward, Alaska. Intrusive masses in sediments of diverse age, Paleozoic to Recent. Except near Iliamna Bay, and Lakes Iliamna and Clark, there has been little prospecting, though much of area is favorable to lode deposits. Some gold, silver, and copper lodes and a few gold placers have been found.

Geology and Ore Deposits of the Montezuma Quadrangle, Colorado. T. S. LOVERING. Pp. 119, figs. 30, pls. 40, incl. maps. U. S. Geol. Surv. Prof. Paper 178. Washington, 1935. $1.25. An important contribution to the geology of the western slope of the Colorado Front Range, especially in regard to the pre-Cambrian formations, Tertiary intrusives, erosion surfaces and thrust faulting. Though some gold has been mined, both placer and lode, the ore deposits are mostly lead-zinc-silver in filled fissures. Vertical zoning is marked. Enrichment is related to old erosion surfaces. The variation of mineralization within the fissures is well illustrated.

Geology and Ground-water Resources of Atascosa and Frio Counties, Texas. J. T. LONSDALE. Pp. 90, pls. 8, incl. geol. map. U. S. Geol. Surv., Water Supply Paper 676. Washington, 1935. 35 cts. Tertiary and Quaternary sediments and water resources of part of Winter Garden district, south-east Texas.

The Underground Geology of the Tonopah Mining District, Nevada. T. B. NOLAN. Pp. 49, map and 2 block diagrams. Univ. of Nevada Bull., vol. 29, no. 5. In co-operation with U. S. Geol. Survey. Reno, 1935. $1.00. Preliminary report of co-operative re-survey of Tonopah district. Combines results of studies in eastern and western parts of district. The faults are described, and relations to ore indicated. An important contribution is the outlining of the productive zone as a relatively thin shell, dome-shaped, and dipping steeply at margins.

Geologic Map of Portion of Country East of Steytlerville, Cape Province, So. Africa. With Explanation by S. H. HAUGHTON. So. African Geol. Surv. Sheet 150 (Sundays River). Pretoria, 1935. 5s. In colors; 1:148,752; covering 1990 sq. miles. Boundary of Cape Folded Belt and Great Karroo. The geology and underground water resources discussed in accompanying explanatory pamphlet (pp. 35).

Gold in Canada, 1935. A. H. A. ROBINSON. Pp. 127, figs. 7, tables 80. Canada Dept. Mines, Mines Branch, 769. Ottawa, 1935. 25 cts. Statistical records through 1934; industrial descriptions of 70 properties. Discussion of metallurgy, history, production, of gold.

SCIENTIFIC NOTES AND NEWS

J. A. Bancroft is consulting geologist for the Anglo American Corporation, with headquarters at Johannesburg.

G. A. F. Molengraaff has received the award of the Wollaston medal of the Geological Society of London.

M. W. Hayward has just returned from geological work in Cuba.

David Gallagher is carrying on a geological survey for the East African Goldfields, Ltd. in Tanganyika.

W. S. Bayley has been elected president of the Mineralogical Society of America.

F. Blondel was recently elected vice-president of the Geological Society of France.

David Sharpstone has opened offices at 1613 Royal Bank Building, Vancouver, B. C., as consulting mining geologist.

J. H. Stowel has taken the place of the late H. P. DePencier as vice-president and general manager of Dome Mines, Ltd.

Stephen Reid Capps, of the U. S. Geological Survey, recently gave a course of lectures in the Grant Memorial Series at Northwestern University, Evanston, Ill.

W. H. Bucher, professor of Historical Geology at the University of Cincinnati, will be exchange professor this season with W. E. Powers of Northwestern University, and will deliver four lectures on structural geology, March 16–19.

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